THE EFFECTS OF PHYSICAL ACTIVITY AND EXERCISE ON COGNITIVE AND AFFECTIVE WELLBEING

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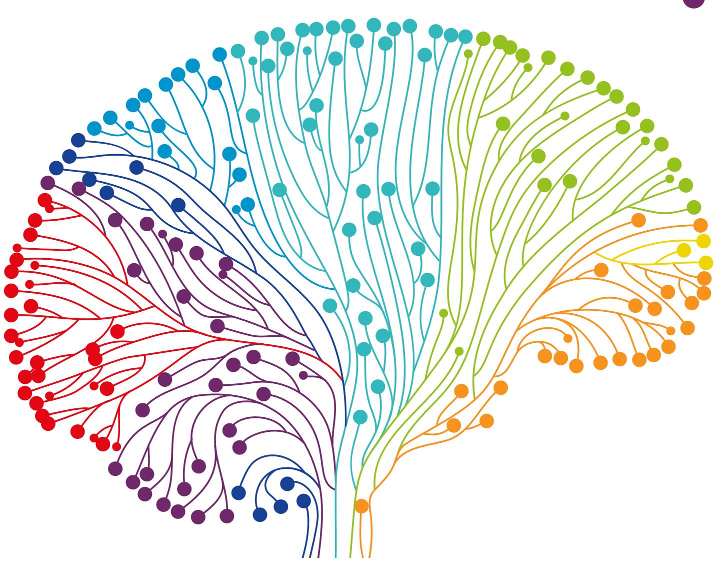
PUBLISHED IN: Frontiers in Behavioral Neuroscience



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ISSN 1664-8714
ISBN 978-2-83250-814-5
DOI 10.3389/978-2-83250-814-5

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THE EFFECTS OF PHYSICAL ACTIVITY AND EXERCISE ON COGNITIVE AND AFFECTIVE WELLBEING

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Citation: Chen, C., Yau, S. Y. S., Clemente, F. M., Ishihara, T., eds. (2022). The Effects of Physical Activity and Exercise on Cognitive and Affective Wellbeing. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-83250-814-5

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frontiers | Frontiers in Behavioral Neuroscience

TYPE Editorial
PUBLISHED 04 November 2022
DOI 10.3389/fnbeh.2022.1047758

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
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SPECIALTY SECTION
This article was submitted to Motivation and Reward, a section of the journal Frontiers in Behavioral Neuroscience

RECEIVED 18 September 2022
ACCEPTED 27 October 2022
PUBLISHED 04 November 2022

CITATION
Chen C, Yau SY, Clemente FM and Ishihara T (2022) Editorial: The effects of physical activity and exercise on cognitive and affective wellbeing. *Front. Behav. Neurosci.* 16:1047758. doi: 10.3389/fnbeh.2022.1047758

Editorial: The effects of physical activity and exercise on cognitive and affective wellbeing

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KEYWORDS

physical activity, green exercise, executive functions, working memory, depression, mental health, neuroimaging, neurobiology

Editorial on the Research Topic
The effects of physical activity and exercise on cognitive and affective wellbeing

A growing body of research suggests that physical activity and exercise enhance a wide range of cognitive and affective wellbeing, including executive functions (Ludyga et al., 2020; Ishihara et al., 2021), memory (Wanner et al., 2020; Aghjayan et al., 2022), creative thinking (Aga et al., 2021; Chen et al., 2021), stress resilience (Arida and Teixeira-Machado, 2021; Belcher et al., 2021), and mental health (Chen et al., 2017; White et al., 2017). Exercise has also been recommended for the treatment of dementia (Cardona et al., 2021) and major depression (Cooney et al., 2013). However, it is still unclear what type, frequency and duration of physical activity and exercise bring the maximal benefits to a specific outcome in a specific population. Furthermore, how findings reported so far can be incorporated into people's everyday life and in educational and psychiatric contexts also remain unaddressed. Finally, the underlying psychological and neurobiological mechanisms of the benefits of physical activity and exercise are still largely unclear. This Research Topic comprises twelve papers that help address these unsolved issues and advance our understanding of the cognitive and affective benefits of physical activity and exercise. Specifically, four important topics emerged from these studies.

Firstly, even a short bout of physical activity or exercise at relatively low intensity may have cognitive and affective benefits. A real-life study by Matsumoto et al. reported that compared to using the elevator, stair-climbing at one's usual pace for three floors roundtrip boosted divergent creative thinking, as assessed by the Alternate Use test.

Ando et al. found that both 30 min of aerobic and resistance exercise at a light intensity (40% peak oxygen uptake) reduced participants' reaction time on a Go/No-Go task that measures executive function. However, changes in cognitive performance were not associated with several peripheral biomarkers, including adrenaline, noradrenaline, cortisol, lactate, etc., which calls for further in-depth investigation on other potential mechanisms underlying the cognitive benefits of physical exercise. Physical activity and exercise at low intensities may also improve mental health and have anti-depressant effects. Legrand et al. found that brisk walking for 30 min either in an urban or a green, natural environment reduced participants' negative affect. However, only walking in the green, natural environment increased participants' positive affect, which emphasized the superior benefits of "green exercise" (Chen, 2018; Li et al., 2022). Given that depressed patients often have reduced exercise motivation and physical fitness, Sakai et al. developed an exercise program consisting of 15–25 min of cycling twice a week at an intensity that approaches but never goes higher than subjects' ventilatory threshold (considered light to moderate in intensity). In a pilot study, the authors reported promising therapeutic effects of this program in depressed patients.

Secondly, the effect of high intensity exercise on cognitive performance may depend on the characteristic of exercise and participants. A review by Sudo et al. found that cognitive performance during acute high intensity aerobic exercise is generally impaired while no impairment and even improvement is observed when cognitive tasks are administered over 6 min after high intensity exercise. They also found that cognitive impairment during high intensity exercise is more likely to occur to individuals with low physical fitness and during cycling than running. Age may be another moderating factor but more research is required to reach sound conclusions. The authors also discussed the underlying mechanism of such cognitive-exercise interaction, including regional cerebral blood flow, cerebral oxygenation and metabolism, neurotransmitters, and neurotrophic factors. In contrast to during high intensity exercise, cognitive performance during moderate intensity exercise may be more likely to be enhanced. In a study by Zheng et al., participants stayed sedentary (seating) or exercised on a cycle ergometer at 50% maximal aerobic power for 15 min while simultaneously performed a n-back task and undergone functional near-infrared spectroscopy (fNIRS). It was found that the reaction time for the n-back task was faster in the cycling than seating condition, which was accompanied by reduced concentration of oxygenated hemoglobin in several brain areas, including the dorsolateral prefrontal cortex. Ballester-Ferrer et al. investigated the effects of a 10-week high-intensity functional training program, in which all-out running, jumping rope, or muscle endurance exercise were performed for 10–30 min, 3 times per week. The authors found that while participants in the control group without such training showed no improvement on reaction time on tasks such as the Choice Reaction Test and Interference Test throughout the 10-week period, participants in the training group demonstrated shorter reaction time on these tasks. However, the effect of the training program on psychological wellbeing was absent.

Thirdly, studies have been using mediation analysis to uncover the mechanisms of the benefits of physical activity and fitness. Potoczny et al. found that the effect of Karate training on satisfaction with life was fully mediated by self-control and reappraisal. Hernández-Jaña et al. found that cardiorespiratory fitness and speed-agility fitness but not muscular fitness mediated the association between BMI/central fatness and cognitive performance on eight tasks evaluating working memory, psychomotor speed, and fluid and logical reasoning, etc. Together with evidence that adiponectin, a hormone released by adipocytes, mediates the antidepressant-like and hippocampal neurogenesis enhancing effect of wheel running in mice (Yau et al., 2014), the latter study highlights the interaction between fitness and fatness in influencing cognitive and affective wellbeing.

Fourthly, given that many individuals especially females (Clemente et al., 2016) are physically inactive, there are a number of ways for people to increase physical activity and use physical activity as a strategy to boost cognitive and affective wellbeing in everyday life. As suggested by Legrand et al., one may want to walk to work or walk for one bus stop while commuting and when walk, one may walk to choose greener routes. As suggested by Matsumoto et al., in the workplace, one may want to take the stairs rather than using the elevator whenever possible. Brown and Kwan suggested another strategy, replacing screen time with physical activity. Using isotemporal substitution analysis, the authors found that replacing screen time with moderate-to-vigorous physical activity or sleep is associated with enhanced mental wellbeing. Furthermore, Shen et al. suggests that rather than pure physical activity, activities that simultaneously require cognitive processing may bring greater benefits. The authors found that 8 weeks of Tai Chi Chuan, a mindfulness exercise that tries to integrate the body and mind, improved inhibitory control performance as indicated by reduced reaction time on a flanker task more than that by 8 weeks of brisk walking. Using resting-state functional magnetic resonance imaging (fMRI), the authors found that the improved inhibitory control performance was correlated with spontaneous neural activity in the left medial superior frontal gyrus. Finally, Almarcha et al. suggests that compared to exercise programs prescribed by other people, co-designed exercise programs with inputs from the participants may bring greater benefits. The authors found that whereas a co-designed 9-week exercise program improved self-reported mental health in seven of eight scales used, a prescribed exercise program improved mental health only in three scales.

Author contributions

All authors contributed to the writing and editing of this Research Topic editorial.

Funding

CC was supported by a research grant from The Nakatomi Foundation, Japan.

Acknowledgments

We would like to thank the authors of all the papers included in this Research Topic as well as the reviewers who helped us evaluate these studies.

Conflict of interest

CC is the author of Cleverland: The Science of How Nature Nurtures.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers in Behavioral Neuroscience

ORIGINAL RESEARCH
published: 08 September 2021
doi: 10.3389/fnbeh.2021.746197

Mediation Role of Physical Fitness and Its Components on the Association Between Distribution-Related Fat Indicators and Adolescents' Cognitive Performance: Exploring the Influence of School Vulnerability. The Cogni-Action Project

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

Received: 23 July 2021
Accepted: 16 August 2021
Published: 08 September 2021

Citation:
Hernández-Jaña S, Sanchez-Martinez J, Solis-Urra P, Esteban-Cornejo I, Castro-Piñero J, Sadarangani KP, Aguilar-Farias N, Ferrari G and Cristi-Montero C (2021) Mediation Role of Physical Fitness and Its Components on the Association Between Distribution-Related Fat Indicators and Adolescents' Cognitive Performance: Exploring the Influence of School Vulnerability. The Cogni-Action Project. Front. Behav. Neurosci. 15:746197. doi: 10.3389/fnbeh.2021.746197

Background: Physical fitness and fatness converge simultaneously modulating cognitive skills, which in turn, are associated with children and adolescents' socioeconomic background. However, both fitness components and fat mass localization are crucial for understanding its implication at the cognitive level.

Objective: This study aimed to determine the mediation role of a global physical fitness score and its components on the association between different fatness indicators related to fat distribution and adolescents' cognitive performance, and simultaneously explore the influence of school vulnerability.

Methods: In this study, 1,196 Chilean adolescents participated (aged 10–14; 50.7% boys). Cardiorespiratory fitness (CRF), muscular fitness (MF), and speed-agility fitness (SAF) were evaluated, and a global fitness score (GFS) was computed adjusted for age and sex (CRF + MF + SAF *z*-scores). Body mass index *z*-score (BMIz), sum-of-4-skinfolds (4SKF), and waist-to-height ratio (WHtR) were used as non-specific, peripheral, and central adiposity indicators, respectively. A global cognitive score was computed based on eight tasks, and the school vulnerability index (SVI) was registered as high, mid or low. A total of 24 mediation analyses were performed according to two models, adjusted for sex and peak high velocity (Model 1), and adding the school vulnerability index (SVI) in Model 2. The significance level was set at $p < 0.05$.

Results: The fitness mediation role was different concerning the fatness indicators related to fat distribution analyzed. Even after controlling for SVI, CRF (22%), and SAF (29%), but not MF, mediated the association between BMIz and cognitive performance. Likewise, CRF, SAF and GFS, but not MF, mediated the association between WHtR and cognitive performance (38.6%, 31.9%, and 54.8%, respectively). No mediations were observed for 4SKF.

Conclusion: The negative association between fatness and cognitive performance is mitigated by the level of adolescents' physical fitness, mainly CRF and SAF. This mediation role seems to be more consistent with a central fat indicator even in the presence of school vulnerability. Strategies promoting physical fitness would reduce the cognitive gap in children and adolescents related to obesity and school vulnerability.

Keywords: cognition, physical activity, children, school, obesity, fatness, fat distribution

INTRODUCTION

An excess of body fat has been associated with a diversity of metabolic, cardiovascular, and mental health conditions (Halfon et al., 2013; Sahoo et al., 2015). Children and adolescents with overweight or obesity present lower cognitive functioning (Esteban-Cornejo et al., 2020) in several cognitive domains such as attention, executive functioning, memory, and visuospatial performance (Liang et al., 2014). An adequate cognitive development in childhood is crucial for both short and long-term, due to its future impact on predictors related to socioeconomic status, health, and behavior, which might counteract the adverse effect of children's social environment (Feinstein and Bynner, 2004).

In this sense, social disadvantages and inequalities have been related to worse cognitive developments and obesity in childhood (Ruiz-Hermosa et al., 2019; Vazquez and Cubbin, 2020). For instance, children and adolescents living in a vulnerable context showed increased cortisol levels, reduced gray and white brain matter, lower performance in working memory, inhibitory control, and cognitive flexibility (Ursache and Noble, 2016b) and thereby, a lower performance in their general cognitive functioning (Hackman and Farah, 2009; Brito and Noble, 2014). Thus, both obesity and social vulnerability converge, affecting normal cognitive development in children and adolescents. This complex scenario might be mitigated in early stages such as adolescence when the brain defines its structure and functioning, and still it is possible to evoke behavioral changes (Herting and Chu, 2017; Stillman et al., 2020).

Many strategies have been suggested to improve children and adolescents' cognitive performance (Diamond and Ling, 2016; Schoentgen et al., 2020). For this purpose, physical fitness seems to be an enjoyable and low-cost approach associated with reducing body fat mass and the influence of social vulnerability (Yang et al., 2007; Åberg et al., 2009). For instance, a study in children aged 5–7 years showed that physical fitness mediates the adverse relationship between body mass index and cognitive performance, and this outcome seems to be independent of socioeconomic vulnerability (Ruiz-Hermosa et al., 2019). Furthermore, a study using a structural equation model established that adolescents' physical fitness mediates the relationship between body mass index and cognitive performance (Lemes et al., 2021). Nonetheless, school vulnerability presented an inverse association with cognitive performance, which was only partially mediated by physical fitness (Lemes et al., 2021). Therefore, current evidence suggests a positive influence of the physical fitness level in the association between fatness and cognitive functioning, which could even be maintained despite the detrimental impact of the children's social background.

Despite this evidence, there are still gaps to cover in order to improve global understanding in this research area. Some authors point out that cardiorespiratory fitness (CRF) has been the most studied fitness indicator on cognition (Esteban-Cornejo et al., 2017; Kao et al., 2017), but scarce evidence has explored how other fitness components such as muscular fitness (MF) and speed-agility fitness (SAF) are related to cognitive functioning. Similarly, fatness indicators have been limited mainly to the use of the body mass index (Ruiz-Hermosa et al., 2019); nevertheless, evidence indicates that the location of fat mass is crucial. For instance, visceral fat seems to affect cognitive functioning to a greater extent than other general (non-specific) or peripheral indicators (Schwartz et al., 2013). Also, longitudinal and bidirectional evidence in children and adolescents have shown that fatness may play a more relevant role in the risk of developing metabolic syndrome compared with CRF (Reuter et al., 2021), and that fatness changes were associated with future CRF levels, independently of baseline CRF (Perez-Bey et al., 2020). The aforementioned, support our theoretical approach considering fatness as a predictor of cognitive performance.

Therefore, the present study aims to determine the mediator role of CRF, MF, SAF, and a global fitness score (GFS) on the association between fatness indicators related to fat distribution such as body mass index *z*-score (BMIz), sum-of-4-skinfolds (4SKF), and waist-to-height ratio (WHtR; non-specific, peripheral, and central adiposity indicators, respectively) and a global cognitive score in adolescents. Furthermore, this study explored the influence of the school vulnerability index (SVI) as a covariate. It is hypothesized that the GFS and all its components mitigate the inverse relationship between fatness indicators and cognitive performance and that mediation effects remain stable even when SVI is included in the model. At the same time, it is hypothesized that WHtR could be the most consistent fat indicator compared to BMIz and 4SKF, in the mediation role of fitness, due to its greater specificity.

MATERIALS AND METHODS

This study is part of the Cogni-Action Project, which determines the associations of physical activity, sedentary behavior, and physical fitness with brain structure and function, cognitive performance, and academic achievement in a large sample of Chilean adolescents (Solis-Urra et al., 2019). It was conducted from March 2017 to October 2019 and involved adolescents from the public, subsidized, and private schools in Valparaíso, Chile. The project was approved by the Ethics Committee of Pontificia Universidad Católica de Valparaíso (BIOEPUCV-H103-2016) and was registered in the Research Registry (ID: researchregistry5791). Written consents or assents were obtained before participation from corresponding school principals, parents, and adolescents. The present study was performed according to STROBE guidelines (Strengthening the Reporting of Observational Studies in Epidemiology) for cross-sectional studies (von Elm et al., 2008).

Study Population

The sample size was calculated based on the total enrolment of children and adolescents between grades 5–8, according to the student universe (n = 951, 962) indicated by the Ministry of Education. More information about sample size estimation can be found elsewhere (Solis-Urra et al., 2019). Overall, a total of 797 participants were needed for representativeness, nonetheless, 1,296 adolescents (10–14 years old) from 19 schools participated in the project. Important to note, this project and study use the definition of adolescence which establishes it as the period between 10–24 years of age (Sawyer et al., 2018). Inclusion criteria for this project were girls and boys from grades 5–8, while the exclusion criteria for this study were incomplete fitness, fatness, cognitive and covariates data. Finally, 1,196 participants were included in this study.

Measurements

Adolescents were evaluated at schools in two sessions of 4 h separated by 8 days. Cognitive performance and anthropometric measurements were assessed in the first session, whereas physical fitness was evaluated in the second session. Trained staff evaluated all variables; moreover, adolescents had familiarization trials before each test.

Physical Fitness Assessment

The ALPHA-fitness test battery was used to evaluate three physical fitness components (CRF, MF, and SAF) by four different field-based tests. The validity and reliability of this battery have been described in previous research (Ruiz et al., 2011). It was suggested to wear suitable sportswear to perform tests in sport or indoor fields during the morning (between 9:30 and 12:00). Instructions were verbally provided, and each test was explained and demonstrated to ensure optimal performance. Adolescents practised the tests and performed them when they felt prepared to start.

Global Fitness Score

To compute the GFS, physical fitness was assessed through the ALPHA fitness test battery, which evaluates three main fitness components, CRF, MF, and SAF (Ruiz et al., 2011). A *z*-score of each component was calculated adjusted for age and sex, and all three were added. The evaluations carried out are detailed below.

Cardiorespiratory Fitness

The 20-m shuttle run test was used to evaluated CRF grouping between eight to 10 participants, and they were guided to the starting line. The run rhythm (pace) was indicated by a sound signal and started at 8.5 km/h, increasing 0.5 km/h every minute. They started the test from the starting line and had to run 20 meters to the second line and wait for the next signal to run back to the starting line. A physical education teacher ran beside the adolescents during the first 2 min to ensure the correct progression and adaptation to the test. The trial ended when participants could not keep the velocity of the test or failed to reach the line twice. Total time in seconds was registered as previously recommended (Tomkinson et al., 2019). Lastly, a *z*-score according to age and sex was created as a normalized CRF score.

Muscular Fitness

The MF indicator was calculated according to upper and lower limb strength. The maximum handgrip strength was used to evaluate upper limb strength using a dynamometer (Jamar Plus+ Digital Hand Dynamometer, Sammons Preston, USA), previously adjusted for participants' hand size (measures of 0–90 kg and 0.1 kg precision). The test was performed on both hands (twice) with a fully extended elbow in a standing position, registering the maximum score. A relative measure of upper limb strength was calculated, dividing the best score (both hands) by body weight.

The standing long jump test was used to determine the lower limb strength. Adolescents must stand with both feet in parallel behind the starting line. They had to jump on the verbal signal as far as possible with both feet simultaneously. They performed twice this test, resting 1 min between attempts, and the longest jump was recorded in centimetres. Lastly, sex- and age-specific *z*-score from the upper and lower limb tests were added to calculate the MF score.

Speed-Agility Fitness

The 4 × 10 m shuttle run test was used to determine SAF, which involves the speed of movement, agility, and coordination. This test consists of running between two lines (5 m in width) separated by 10 m in length, with both lines having a cone placed as a point reference. Every participant had to run as fast as possible, and on reaching the first line, they had to grab a cloth located ∼50 cm and run back, carrying it to the start line (this procedure was repeated three times). After that, they had to repeat the sequence until the ending of the test. Every adolescent had two opportunities, and the fastest time was recorded in seconds. Furthermore, time was multiplied by −1; a higher score means a better performance. Lastly, a *z*-score according to age and sex was created as a normalized SAF score.

Cognitive Performance

Cognitive performance was evaluated using the NeuroCognitive Performance Test (NCPT) from Lumos Labs, Inc., which has demonstrated acceptable reliability and validity to assess cognitive performance (Morrison et al., 2015). This test based on a web-based platform allows measuring several cognitive domains such as working memory, visuospatial memory, psychomotor speed, fluid and logical reasoning, response inhibition, numerical calculation, and selective and divided attention.

The NCPT was taken in groups of 25 participants (each one had a laptop provided by the research team) in school classrooms, lasting roughly 1 h the entire session. First of all, the session's objective was provided through a brief explanation, demonstration, practice, and execution before each test. Furthermore, any adolescents' questions about the procedure were immediately answered by an instructor before starting each cognitive test. A summary of all cognitive tests is shown in **Supplementary Figure 1**, and more information about them can be found in previous research (Morrison et al., 2015; Solis-Urra et al., 2019). Finally, following the original battery procedure, each test was scaled according to a normal inverse transformation of the percentile rank (Morrison et al., 2015). Hence, it calculated a score derived on the same normal distribution with a mean and standard deviation of 100 and 15.

Fatness Indicators

General and non-specific indicator of adiposity (BMIz): The height and weight were measured with a digital scale OMRON (HN-289-LA, Kyoto, Japan) with a precision of 0.1 kg and a portable stadiometer SECA (model 213, GmbH, Germany) with a precision of 0.1 cm, respectively. The World Health Organization, 2007 growth reference was used to determinate BMIz for school-age children (de Onis et al., 2007).

Peripheral adiposity indicator (4SKF): Triceps, biceps, subscapular, and suprailiac skinfolds were measured with a Slim Guide calliper (Creative Health Products, Plymouth, Michigan, United States) and added to calculate the 4SKF (Cristi-Montero et al., 2019).

Central adiposity indicator (WHtR): The minimum waist circumference was assessed with an inextensible tape (Lufkin, Apex, NC, Unites States), and then it was divided by height in centimetres to obtain WHtR (waist[cm]/height [cm]).

Covariates

Sex, peak high velocity (PHV), and SVI were used as covariates. Sex has been considered a relevant moderator in this research area because visceral fatness, for instance, may impact more strongly in female subjects (Schwartz et al., 2013). Likewise, there is a significant interindividual variance in biological maturation timing among adolescents (Lloyd et al., 2014). Thereby, differences between chronological and biological age would be reflected in brain development or cognitive abilities (Brown et al., 2012). Hence, PHV was calculated as a maturity indicator (Moore et al., 2015), subtracting the PHV age from the chronological age. Differences among years were established as a maturity offset value.

Socioeconomic status is a potent predictor of diverse domains such as language skills, executive function, memory, and social-emotional processing (Ursache and Noble, 2016a). However, in Latin-American countries, school characteristics (i.e., economic, social, and cultural status) seem to be a stronger predictor of adolescents' cognitive and school performance than socioeconomic status (Flores-Mendoza et al., 2015). SVI is an index to measure students' socioeconomic vulnerability at public/subsidized funding schools. It involves the family's socioeconomic status, the educational level of parents-tutors, student health condition, physical and emotional wellbeing, and school location (López et al., 2017). Then, schools were classified as low (<10), middle (≥ 10 to <60), and high (≥ 60) SVI. A value of zero is assigned to private schools.

Statistical Analysis

Descriptive statistics are shown as mean and standard deviation. Parametric tests (*t*-student, correlations, and mediations) were used to conduct all analyses, as indicated by the central limit theorem for sample sizes over 500 participants (Lumley et al., 2002). Simultaneously, a Q-Q plot (quantile-quantile plot) was used for checking normality visually. Neither interaction by sex nor by age was observed, thereby all analyses are presented together for boys and girls and adolescents between 10 and 14 years old. However, **Table 1** (participants' characteristics) gives information about boys, girls, and all together to have a global vision of the study participants.

The t-Student test was performed to compare boys' and girls' characteristics. Associations among fatness indicators, fitness components, and cognitive performance were performed by Pearson correlations (continuous variables) and Kendall's tau-b to SVI (categorical variable). Moreover, multicollinearity was checked before performing the mediation analysis. Considering the high rate of participation and representativeness, missing data were not imputed.

The mediation model is presented in **Figure 1**. Overall, 24 mediation analyses were performed considering predictors (BMIz, 4SKF or WHtR), mediators (global fitness, CRF, MF, or SAF), outcome (cognitive performance), and two models (covariates). The general mediation model was structured as follows: equation (a) consisted of the predictor by the mediator;

TABLE 1 | Participants' characteristics.

	All		Boys		Girls		
	n	**Mean ± SD**	***n***	**Mean ± SD**	***n***	**Mean ± SD**	***p*-value**
Age (years)	1,196	11.71 ± 1.06	606	11.68 ± 1.05	590	11.74 ± 1.08	0.312
Weight (kg)	1,183	50.28 ± 11.91	603	49.38 ± 11.99	580	51.21 ± 11.76	**0.002**
Height (cm)	1,183	152.41 ± 9.24	603	152.24 ± 10.19	580	152.57 ± 8.13	0.206
PHV	1,183	−0.55 ± 1.21	603	−1.28 ± 0.93	580	0.21 ± 0.98	**<0.001**
BMIz	1,183	1.04 ± 1.07	603	1.07 ± 1.10	580	1.01 ± 1.03	0.244
4SKF (mm)	1,150	64.56 ± 27.47	587	57.05 ± 23.77	563	72.40 ± 28.87	**<0.001**
WHtR	1154	0.46 ± 0.06	587	0.46 ± 0.06	567	0.45 ± 0.06	**<0.001**
SVI	1,196	56.08 ± 35.12	606	57.61 ± 34.16	590	54.51 ± 36.04	0.128
Cognitive performance	1,196	100.02 ± 4.85	606	99.70 ± 4.88	590	100.34 ± 4.80	**0.021**
Global fitness score	912	0.01 ± 3.10	460	−0.01 ± 3.21	452	0.03 ± 2.98	0.845
CRF (zscore)	967	0.00 ± 1.00	491	0.00 ± 1.00	476	0.00 ± 1.00	0.602
MF (zscore)	975	0.02 ± 1.68	489	0.03 ± 1.73	486	0.02 ± 1.62	0.960
SAF (zscore)	976	0.00 ± 1.00	492	0.00 ± 1.00	484	0.00 ± 1.00	0.689

SD, standard deviation; PHV, peak high velocity; BMIz, body mass index (zscore); 4SKF, sum-of-4-skinfolds; WHtR, waist-to-height ratio; SVI, school vulnerability index; CRF, cardiorespiratory fitness; MF, muscular fitness; SAF, speed-agility fitness. Bold values indicate statistical significance.

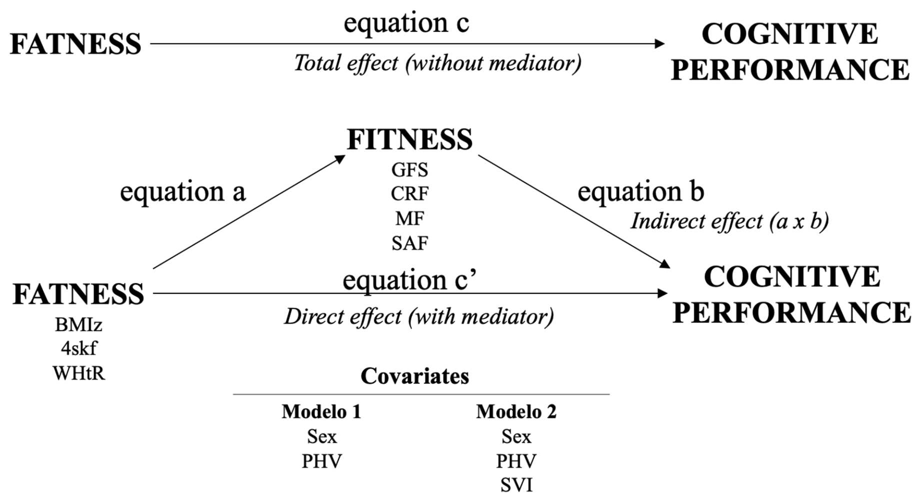

FIGURE 1 | Theoretical approach and general mediation model. BMIz, body mass index (zscore); 4SKF, sum-of-4-skinfolds; WHtR, waist-to-height ratio; GFS, global fitness score; CRF, cardiorespiratory fitness; MF, muscular fitness; SAF, speed-agility fitness; PHV, peak high velocity; SVI, school vulnerability index.

equation (b) was defined as a mediator by the outcome; equation (c) consisted of the predictor by the outcome; and finally, equation (c') consisted of predictor and mediator by the outcome. Bias was reduced, adjusting analyses to relevant covariates; thus, two models were performed to test our objectives and hypotheses. Model 1: adjusted for sex and PHV, and model 2: adjusted for sex, PHV, and SVI. Note that: (a) the models were not adjusted for other fitness components to facilitate comparison between the percentage of mediation with the GFS (composed by the sum of the three fitness components); and (b) sample size by analysis changes depending on if participants have measures of all their variables (fatness, fitness, cognitive and covariates). Detailed sample size by analysis is presented as **Supplementary Material** (**Supplementary Tables 1–3**).

To evaluate the mediation effect, bootstrapping with 5,000 samples linear regression analysis was performed (Preacher and Hayes, 2008) through PROCESS SPSS script (Hayes, 2013). The indirect effect was considered significant if zero was outside the 95% confidence interval (Field, 2013). Percentage of mediation was estimated as 1– (equation c' / equation c). Finally, the mediation was classified according to Nitzl et al. (Nitzl et al., 2016) as: (a) "Indirect-only" (Full mediation): the indirect effect only exists through the mediator, this means the indirect effect exists, but no direct effect; (b) "Complementary" (Partial mediation): a portion of the effect of the predictor on the outcome variable is mediated through the mediator, whereas predictor still explains a portion of outcome variable that is independent of a mediator, that means that the indirect and direct effect exists and point in the same direction; (c) "Competitive" (Partial mediation): the same as the complementary classification, both the indirect and direct effect exists but point in different directions; (d) "Direct-only" (No mediation): the direct effect exists, but no indirect effect; and (e) "No effect" (No mediation): neither direct and indirect effect exists (Zhao et al., 2010). For all analyses, the significance level was set at $p < 0.05$.

RESULTS

Table 1 displays participants characteristics and differences by sex (boys 50.7% and girls 49.3%). Statistical differences in weight, PHV, WHtR, 4SKF and cognitive performance were found.

The correlation matrix among fatness indicators (i.e., BMIz, 4SKF, WHtR), fitness indicators (i.e., GFS, CRF, MF and SAF), SVI and cognitive performance are presented in **Table 2**. Overall, all physical fitness variables were negatively correlated with fatness indicators. In contrast, physical fitness variables were positively associated with cognitive performance, and fatness variables were negatively related to cognitive performance. Moreover, all correlations were statistically significant.

Table 3 shows a summary of all study mediations. Overall, it is possible to observe the variation in each meditation percentage and classification according to model 1 and 2. For BMIz: both CRF and SAF presented a "complementary" mediation (model 1) which changed to "Indirect only" mediation in model 2. The final mediation percentages (model 2) were 22.0% (SAF) and 29.0% (CRF). GFS and MF did not have any mediation effect after controlling for SVI (model 2). In 4SKF: the global fitness and all its components did not mediate the association between 4SKF and cognitive performance after controlling the analysis for SVI (model 2). For WHtR: GFS, CRF, and SAF presented a full mediation effect ("Indirect only") in both models. The final mediation percentages (model 2) were 31.9% (SAF), 38.6% (CRF), and 54.8% (GFS). MF did not have any mediation effect. A complete description of all mediation analyses is presented as **Supplementary Material** (**Supplementary Tables 1–3**).

DISCUSSION

This study aimed to determine the mediation role of a GFS and its components on the association between different fatness indicators related to fat distribution and a global cognitive score in adolescents and exploring the influence of SVI. Concerning the mediations, first, the influence of physical fitness as a mediator was modified according to what kind of fatness indicator related to fat distribution was analyzed; second, the GFS, CRF, and SAF showed a significant mediation role, whereas MF did not; and third, the SVI inclusion in the second model tends to modify the percentage and mediation's classification; nonetheless, the favorable fitness role in the association between WHtR and cognitive performance seems to not be affected.

Differences in Fitness Component Mediations

To date, the positive association between physical fitness and cognition is well-established in the literature (Donnelly et al., 2016). However, it is crucial in this research area to expand the exploratory approach to multiples fitness components due to the personal preferences of type of exercise and physical activities (which could improve a particular fitness component more than others), and also due to the differential association between each fitness component with cognitive skills. Regarding the latter, a study in children with overweight and obesity showed a positive association between MF and planning ability, between SAF and cognitive flexibility and inhibition, and finally CRF and a GFS with indicators of cognitive flexibility (Mora-Gonzalez et al.,

TABLE 2 | Correlation matrix among fatness, fitness, and cognition variables.

	BMIz	4SKF	WHtR	GFS	CRF	MF	SAF	SVI
4SKF	**0.730**							
WHtR	**0.830**	**0.724**						
GFS	**−0.425**	**−0.475**	**−0.467**					
CRF	**−0.341**	**−0.399**	**−0.349**	**0.789**				
MF	**−0.458**	**−0.496**	**−0.511**	**0.906**	**0.558**			
SAF	**−0.208**	**−0.236**	**−0.235**	**0.785**	**0.496**	**0.547**		
SVI	**0.089**	**0.054**	**0.126**	**−0.160**	**−0.139**	**−0.184**	**−0.054**	
Cognitive performance	**−0.102**	**−0.094**	**−0.102**	**0.133**	**0.124**	**0.094**	**0.109**	**−0.146**

BMIz, body mass index standard deviation; 4SKF, sum 4 skinfolds; WHtR, waist-to-height ratio; GFS, global fitness score; CRF, cardiorespiratory fitness; MF, muscular fitness; SAF, speed-agility fitness; SVI, school vulnerability index. Bold values indicate statistical significance.

TABLE 3 | Findings' summary concerning the direct and indirect effect according to both models.

	BMIz	4SKF	WHtR
GFS	**43.5%* → 36.9% = Δ −6.6** Indirect only → No effect	**40.8% → 31.8% = Δ −9.0** No effect → No effect	**51.8%* → 54.8* = Δ +3.0** Indirect only → Indirect only
CRF	**32.5%* → 29.0%* = Δ −3.5** Complementary → Indirect only	**34.8% → 29.2% = Δ −5.6** Direct only → No effect	**36.4%* → 38.6%* = Δ +2.2** Indirect only → Indirect only
MF	**26.3% → 9.7% = Δ −16.6** Direct only → No effect	**23.0% → 3.0% = Δ −20.0** Direct only → Direct only	**31.8% → 19.1% Δ −12.7** No effect → No effect
SAF	**19.7%* → 22.0%* = Δ +2.3** Complementary → Indirect only	**19.0% → 19.7% = Δ +0.7** Direct only → Direct only	**23.1%* → 31.9%* = Δ +8.8** Indirect only → Indirect only

***General scheme: Model 1 → Model 2** = Variation on mediation (Δ %); Model 1: Adjusted for sex and PHV; Model 2: Adjusted Model 1 + SVI. * indicates the indirect effect is statistically significant. 4SKF, sum-of-4-skinfolds; BMIz, Body Mass Index z-score; WHtR, Waist-to-Height Ratio; GFS, global fitness score; CRF, Cardiorespiratory Fitness; MF, Muscular Fitness; SAF, Speed-Agility Fitness. Mediation classifications: "Indirect-only" (Full mediation): the indirect effect only exists through the mediator, which means the indirect effect exists, but no direct effect; "Complementary" (mediation): indirect and direct effect exists and point in the same direction; "Indirect-only" (mediation): indirect effect exists, but no direct effect; "Direct-only" (non-mediation): direct effect exists, but no indirect effect; and "No effect" (non-mediation): neither direct and indirect effect exists. Percentage of mediation and classification.*

2019). Another study based on the same sample of the present study showed that CRF, MF and SAF differed in their significant association according to the cognitive domain studied (cognitive flexibility, working memory, inhibitory control, or intelligence; Solis-Urra et al., 2021). In this sense, our findings showed that the GFS, CRF, and SAF were positively associated with the global cognitive score and mediated the relation between fatness and cognition. However, MF did not mediate any association.

These fitness component differences could be explained to a certain extent by the physiological influence of each one of them on brain indicators and also mechanisms related to fat oxidation. On the one hand, activities with a high CRF demand seem to activate the prefrontal cortex and the hippocampus and increase neurotrophins related to neurogenesis and angiogenesis at the cerebral level (Best, 2010). Indeed, children having a high CRF show greater total gray and white matter volume (Cadenas-Sanchez et al., 2020). This positive association between CRF and brain indicators also was observed in MF, SAF, and GFS. MF has been less studied, being its influence on brain functioning related to a direct neuromuscular mechanism boosting the strength and power demand, which seems to be dependent on the muscular contraction type (Yao et al., 2016; Solis-Urra et al., 2021). However, the MF influence in a whole-brain volumetric approach in children seems to not be independent of CRF (Esteban-Cornejo et al., 2017, 2021). In contrast, SAF involved speed of movements, agility, coordination, and a mix between power, strength and aerobic capacity which elicit high cognitive demands (Best, 2010; van der Fels et al., 2015). Hence, this study speculates that all differences mentioned could affect the variation in the mediations found in our study.

On the other hand, these fitness components in children and adolescents are developed through a diversity of physical activities (games, sports, physical education classes, active commuting, etc.) being difficult to isolate the development of a particular fitness component; however, there is a certain specificity in some physical activities. Thus, in addition to activating diverse brain zones to execute complex motor movements (Best, 2010), physical activities with higher intensity and duration can significantly increase the energy demand, which, in turn, improves fat oxidation (Chang et al., 2021), unlike strength exercises which have shown to be less effective (Chang et al., 2021). Thereby, recommendations to increase physical activity focusing on physical fitness improvement in children and adolescents are crucial to enhance their cognitive functioning through the direct influence of exercise and physical activity and indirectly, reducing the detrimental impact of fat on health.

Fatness Indicators Related to Fat Distribution

Our findings reinforce the relevance of studying fatness indicators related to its distribution, showing that the fitness mediator role depends on the fatness indicator studied. Overall, excess adiposity in children and adolescents has been linked to higher inflammatory markers, which in turn, is a risk factor for neurodegeneration and cognitive impairment (Trollor et al., 2012; Caminiti et al., 2016). However, the three fatness indicators used in this study, which involved non-specific (BMIz), peripheral (4SKF), and central body fat distribution markers (WHtR), differ in their level of association with respect to the low-grade inflammation, becoming more pronounced as age advances (Cabral et al., 2019a,b). Thus, BMIz must be considered as a surrogate marker for obesity which does not differentiate between peripheral and central obesity, while between 4SKF and WHtR, the latter seems to be more related to inflammation and cognitive functioning (Caminiti et al., 2016).

In this sense, our results support the notion that physical fitness' mediation role, mainly CRF and SAF, was more sensitive to WHtR followed by BMIz (no mediation with 4SKF). On one hand, metanalytic studies have concluded that interventions including exercise showed to be more effective in reducing visceral adiposity, regardless of the total body weight loss (Verheggen et al., 2016); and in children and adolescents with obesity, it was also observed that exercise is more effective than diet alone or than the combination between diet and exercise to reduce visceral fat (Verheggen et al., 2016; Vissers et al., 2016). On the other hand, a network meta-analysis showed that high-intensity interval training and aerobic exercise (between 30–60 min duration/session) were the most effective strategies to reduce visceral fat compared to strength exercise (Chang et al., 2021). Hence, this study speculates that, first, the mediation effect found in BMIz could be a consequence of the central fat included in this marker; and second, children and adolescents who accumulated more physical activities show increased CRF, SAF, and the GFS, which would consequently enhance the efficacy to oxidase and reduce visceral fat (Perez-Bey et al., 2020) and, in turn, influence cognition.

Exploring SVI

A novel approach of the present study was to explore an indicator of vulnerability due to their implication in fatness, fitness and cognitive outcomes in children and adolescents (Jiménez-Pavón et al., 2010; Ursache and Noble, 2016a). Our findings show that SVI has a differentiated influence according to the model analyzed. For BMIz, SVI reduced all mediation effects except for SAF. However, CRF and SAF mediator role kept their statistical significance (29% and 22%, respectively). In the case of WHtR, a different scenario was present because the SVI inclusion increased the mediation role of the GFS, CRF, and SAF (Δ 3.0%, Δ 2.2%, and Δ 8.8%, respectively). All of them kept their statistical significance. Thus, on the one hand, these findings support our hypothesis showing the higher WHtR's specificity compared to 4SKF and BMIz; and on the other hand, they support CRF and SAF's relevant role regardless of adolescents' school vulnerability influence.

The aforementioned is valuable to public health policy and educative communities, allowing to reduce the cognitive gap associated with children's social background and obesity. Therefore, physical activity and physical fitness programs could be an efficient and low-cost strategy to improve cognition performance in children and adolescents, reducing the detrimental impact of fatness indicators and school vulnerability.

Strengths and Limitations

A strength of this study is its large sample size of adolescents from a Latin-American country. This study has also included a full assessment of several fatness and fitness indicators that increase understanding in this research area. This study has used a robust cognitive score calculated by eight different tasks. Finally, exploring the influence of a vulnerability score allows this study to establish a novel finding with respect to the mediator role of fitness regardless of the adolescents' social background profile. Nonetheless, this study has some limitations; first, its cross-sectional design implies that the cause-effect relationships among variables cannot be determined. Second, physical fitness was evaluated by field-based tests due to the high costs of gold-standard methods. Lastly, fatness was evaluated by a double indirect method, which could increase methodological biases. However, both fitness and fatness measures are feasible to implement in school settings.

Conclusion

It is concluded that a higher level of physical fitness, mainly CRF and SAF, would mediate the detrimental influence of fatness on adolescents' cognitive performance. The fatness indicator related to central fat distribution seemed to be more consistent, both theoretically and statistically. Finally, the mediator role of physical fitness in adolescents' cognitive performance remains constant even in the presence of an important school vulnerability indicator, highlighting that it might play a relevant protective social role. Thereby, public health and educational strategies promoting physical fitness improvement through a wide diversity of physical activities are a determining factor in the reduction of the cognitive gap caused by obesity and social vulnerability in children and adolescents.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Bioethics and Biosafety Committee of the Pontificia Universidad Católica de Valparaíso (BIOEPUCV-H103-2016). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

CC-M contributed to the design of the project and is the corresponding author. CC-M and SH-J conceptualized the design of the study. SH-J and CC-M analyzed the data and wrote the concept version of the manuscript. JS-M, PS-U, IE-C, JC-P, KS, NA-F, and GF critically reviewed the manuscript and edited the article. All authors have given final approval of the manuscript and agreed to be accountable for the accuracy and integrity of any part of the work. All authors contributed to the article and approved the submitted version.

FUNDING

The "Cogni-Action Project" was supported by the National Commission for Scientific and Technological Research CONICYT/FONDECYT INICIACION 2016 grant no. 11160703. IE-C was supported by the Spanish Ministry of Science and Innovation (RYC2019-027287-I).

ACKNOWLEDGMENTS

We thank schools, parents, adolescents, and collaborators who selflessly participated in our project.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnbeh.2021.746197/full#supplementary-material.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Behavioral Neuroscience

ORIGINAL RESEARCH
published: 05 October 2021
doi: 10.3389/fnbeh.2021.736587

Movement Behaviors and Mental Wellbeing: A Cross-Sectional Isotemporal Substitution Analysis of Canadian Adolescents

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OPEN ACCESS

Edited by:
Filipe Manuel Clemente, Polytechnic Institute of Viana do Castelo, Portugal

Reviewed by:
Chong Chen, Federal University of Mato Grosso, Brazil

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Specialty section:
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

Received: *05 July 2021*
Accepted: *06 September 2021*
Published: *05 October 2021*

Citation:
Brown DMY and Kwan MYW (2021) Movement Behaviors and Mental Wellbeing: A Cross-Sectional Isotemporal Substitution Analysis of Canadian Adolescents. Front. Behav. Neurosci. 15:736587. doi: 10.3389/fnbeh.2021.736587

Background: Studies have shown reallocating screen time for healthy movement behaviors such as physical activity and sleep can provide important benefits for mental health. However, the focus on positive aspects of mental health such as wellbeing has received limited attention, particularly among adolescents. The purpose of this study was to examine the effects of reallocating physical activity, screen time, and sleep on mental wellbeing in adolescents.

Methods: This study involved cross-sectional analysis of data from Wave 1 of the ADAPT study. A total of 1,118 Canadian adolescents enrolled in grade 11 classes (M_{AGE} = 15.92; 54.5% female) self-reported their movement behaviors using the International Physical Activity Questionnaire – Short Form to assess moderate-to-vigorous physical activity and daily recall questionnaires to assess recreational screen time and sleep. Participants also completed three measures of mental wellbeing: the Flourishing Scale, Rosenberg Self-Esteem Scale, and a brief Resiliency scale from the Canadian Campus Wellbeing Survey.

Results: Isotemporal substitution analysis revealed replacing 60 min of screen time with either moderate-to-vigorous physical activity or sleep has significant benefits for mental wellbeing. Comparatively, reallocating 60 min between moderate-to-vigorous physical activity and sleep does not impact mental wellbeing.

Discussion: Findings suggest healthy movement behaviors confer similar beneficial effects for adolescent's mental wellbeing. Health promotion campaigns targeted toward adolescents should consider highlighting that reallocation of screen time to either sleep or moderate-to-vigorous physical activity may provide important benefits for mental wellbeing.

Keywords: mental health, physical activity, screen time, sleep, daily time use

INTRODUCTION

The 24-h movement behavior paradigm is a relatively novel approach that considers how all types of movement behaviors – physical activity, sedentary behaviors, and sleep – collectively contribute to the healthy development of children and youth (Tremblay et al., 2016). This approach builds on previous work that typically examined independent associations between time spent in each movement behavior and health outcomes, and in doing so, accounts for the codependence among these behaviors over the course of a whole day (i.e., during the 24-h period) (Tremblay and Ross, 2020). Recent systematic reviews have shown engaging in a lifestyle consisting of adequate amounts of physical activity and sleep, in addition to a small amount of time spent engaging in sedentary behaviors such as recreational screen time has significant benefits for several important health indicators during the early life stages (Rollo et al., 2020; Sampasa-Kanyinga et al., 2020). Although research to date has largely focused on relationships between movement behaviors and physical health outcomes (e.g., adiposity, cardiometabolic health, aerobic fitness), indicators of mental health have begun to see increased attention of late, particularly among adolescents (Carson et al., 2016, 2017; Janssen et al., 2017; Knell et al., 2019; Pearson et al., 2019; Zhu et al., 2019; Bang et al., 2020; Faulkner et al., 2020; Patte et al., 2020; Brown et al., 2021a,b; Gilchrist et al., 2021; Sampasa-Kanyinga et al., 2021), yet critical knowledge gaps in our understanding of the movement behaviors – mental health relationship remain.

Understanding the impact of movement behaviors on mental health during the adolescent period is of particular importance from a public health standpoint as this life stage is characterized by heightened stress (Spear, 2000) and represents the peak onset of mental health problems (Kessler et al., 2007; Paus et al., 2008). Mental health, however, has been proposed to exist on a continuum that considers not only adverse symptoms, but also positive attributes (Keyes, 2002). From this perspective, it is equally as important that we establish empirical links between movement behaviors and mental wellbeing. Importantly, existing evidence suggests flourishing, self-esteem and resiliency – three indicators of mental wellbeing – may provide protective benefits against stress and the development of mental health problems such as depression and anxiety (Keyes, 2006; Orth et al., 2008; Hjemdal et al., 2011; Skrove et al., 2013; Kwok et al., 2014; Anyan and Hjemdal, 2016; Henriksen et al., 2017; Masselink et al., 2018; Doré et al., 2020).

To date, movement behaviors have been found to be associated with mental health and wellbeing (Sampasa-Kanyinga et al., 2020). However, the evidence has largely been based on adherence (or not) to each of the threshold-based 24-h movement guidelines (Carson et al., 2016, 2017; Janssen et al., 2017; Knell et al., 2019; Pearson et al., 2019; Zhu et al., 2019; Bang et al., 2020; Faulkner et al., 2020; Patte et al., 2020; Sampasa-Kanyinga et al., 2021), with findings generally indicating that concurrent adherence to all three threshold-based guidelines is associated with more favorable mental health and wellbeing than meeting two or fewer guidelines (Sampasa-Kanyinga et al., 2020). This approach is important from a behavioral surveillance standpoint in that it can provide population-level information about the proportion of adolescents meeting public health-based recommendations, but it is not without its limitations. For instance, using dichotomous cut-point criteria sacrifices a substantial amount of information about movement behaviors that may contribute to variability in indicators of mental health. This approach also fails to provide insight regarding what occurs when time spent in one movement behavior displaces another (e.g., staying up late to watch TV rather than sleep). Isotemporal substitution modeling is an alternative integrative approach that has been recommended to address these specific limitations (Chaput et al., 2017).

Isotemporal substitution modeling is particularly useful when considering 24-h movement guidelines, as time use across the course of a day is finite (i.e., cannot exceed 24-h). Therefore, engaging in one movement behavior comes at the cost of not engaging in other movement behaviors (Mekary et al., 2009). For example, if an adolescent wanted to go from being inactive to meeting the 24-h movement recommendation of 60 min of moderate-to-vigorous physical activity (MVPA) each day, then their combined time spent engaging in sedentary behaviors or sleep would be need reduced by 60 min. In addition to evaluating the reallocation of time spent in one movement behavior with another, the isotemporal substitution model also adjusts for the confounding effects of the remaining time use components (Mekary et al., 2009).

The authors of a recent systematic review of isotemporal substitution modeling of movement behaviors and related health outcomes highlighted that there is a dearth of studies related to mental health (Grgic et al., 2018). Evidence among adolescents is particularly limited, as only one study was found to have replaced time spent playing sedentary video games with active video games or active outside play was associated with positive influences on adolescent's mental health (Janssen, 2016). However, this study failed to consider the full compliment of movement behaviors, as sleep was not assessed. Recently, there has been another study using cross-sectional data from over 46,000 students participating in the COMPASS Study. This study by Gilchrist and colleagues (2021) found that the benefits of reallocating 15 min of any type of behavior is moderated based on whether an adolescent meets the sleep guidelines. In other words, they found that replacing screen time with either homework, MVPA or sleep was generally associated with lower scores for anxiety and depression and higher scores for flourishing; however, the magnitudes of the effects for sleep were greatest when adolescents were not acquiring an average of 8 h of sleep each night. This seminal work established important empirical links between movement behaviors and flourishing, but additional research examining other indicators of mental wellbeing is needed to address key gaps in our current understanding. Therefore, the purpose of the current study was to examine the effects of reallocating physical activity, screen time, and sleep on indicators of mental wellbeing among a sample of Canadian adolescents. In line with previous research examining the relationship between movement behaviors and flourishing (Gilchrist et al., 2021), we hypothesized that replacing screen time with healthier movement behaviors (i.e., sleep and MVPA) would be associated with better mental wellbeing among adolescents getting less than the recommended amount of sleep, whereas among those getting enough sleep, replacing screen time and sleep with MVPA would result in better mental wellbeing.

MATERIALS AND METHODS

Study Sample and Data Collection

The present study utilized baseline data from the ADAPT study: Application of integrated Approaches to understanding Physical activity during the Transition to emerging adulthood (Kwan et al., 2020). This is a 4-year, prospective longitudinal study tracking a sample of Canadian adolescents as they transition out of high school and into emerging adulthood in order to gain an understanding of factors underlying changes in physical activity behavior. At baseline, all grade 11 students enrolled into one of the seven secondary schools across a large school board in Southern Ontario were invited to take part in the study. Participation in the study was voluntary, and informed consent was obtained online from each participant prior to data collection at each individual school in the Fall/Autumn term. Students willing to participate completed a 20-min online survey during class time. Parental consent, collected by paper or electronically, was also a requirement for their data to be included in the study. More information about the recruitment strategy and study protocol can be found elsewhere (Kwan et al., 2020). The protocol for the ADAPT study was approved by both the Institutional Research Ethics Board and the School Board Ethics Committee.

Among the 2,412 enrolled at one of the seven secondary schools within the school board, 1,585 agreed and provided consent to participate (66% response rate). Of the 1,585 consenting students, 146 respondents (9%) withdrew their participation (i.e., completed >5% of the survey), while 186 respondents (12%) did not have parental consent for their participation. As a result, the final baseline sample in the current study included 1,253 participants. Among the total baseline cohort, 1,165 participants (93%) had full data for the variables of interest and covariates used in our analyses. Missing data included 16 cases for movement behaviors (1%), 34 (3%) for at least one mental wellbeing variable, 26 (2%) for gender, and 12 (1%) for parental education. Missing data was handled using listwise deletion. Additionally, 47 participants reported amounts of physical activity, recreational screen time and sleep that totaled over 24 h, and were therefore removed from the present analysis, resulting in data for a total of 1,118 participants included in this study.

Measures

Demographics

Participants completed a demographic questionnaire assessing their age, gender, ethnicity, and highest level of parental education. For analyses purposes, ethnicity was dummy coded into White (1) and other (0), and parental education was dummy coded into college/university graduate (1) and partial completion of post-secondary education or less (0). Parental education was used as a proxy indicator of socioeconomic status.

Movement Behaviors

In accordance with the Canadian 24-Hour Movement Guidelines for Children and Youth (1), movement behaviors were operationalized as a latent construct consisting of MVPA, screen time and sleep. The present study only focused on the three threshold-based components of the 24-h cycle despite recommendations for engaging in several hours of light physical activity also included within the guidelines.

Moderate-to-Vigorous Physical Activity

Moderate-to-vigorous physical activity was measured using the International Physical Activity Questionnaire – Short Form (Booth, 2000; Craig et al., 2003). Participants responded to four items that assessed the frequency (days) and duration (hours and/or minutes on an average day) of their moderate and vigorous physical activity performed in bouts of greater than 10-min over the past 7 days. The International Physical Activity Questionnaire – Short Form defines moderate physical activity as “activities that take moderate physical effort and make you breathe somewhat harder than normal” and provides carrying light loads, bicycling at a regular pace, and playing doubles tennis, but not walking, as examples of activities that involve moderate physical effort. As per the International Physical Activity Questionnaire – Short Form, vigorous physical activity is defined as “activities that take hard physical effort and make you breathe much harder than normal,” with heavy lifting, digging, aerobics, or fast bicycling provided as examples. Daily MVPA was calculated by multiplying frequency by duration for moderate and vigorous physical activity, respectively, and then summing these products and dividing by seven. The International Physical Activity Questionnaire – Short Form has shown acceptable measurement properties when administered among adolescents (Guedes et al., 2005).

Screen Time

Screen time was assessed using a standard daily recall questionnaire that asked participants how much time (hours and/or minutes) on average they spent watching TV or using a computer, tablet or smartphone during their free time over the past 7 days.

Sleep

Participants responded to four items that assessed what time they typically went to sleep and woke up during weekdays and on the weekend over the past 7 days. Responses were used to calculate the average number of hours participants slept on weekdays and weekends. Average daily sleep was then calculated by multiplying weekday sleep by five and weekend sleep by two, and then summing these products and dividing by seven. Although sleep quality may provide additional insight that could be used to understand the relationship between sleep and mental health (João et al., 2018), recommendations provided in the 24-Hour Movement Guidelines for Children and Youth focus on sleep duration – 8 to 10 h for youth – for healthy development.

Flourishing

Flourishing was measured using the Flourishing Scale (Diener et al., 2010), which provides a summary measure of the respondent's self-perceived success in important aspects of their life including relationships, purpose and optimism. This measure has demonstrated strong psychometric properties when administered to youth (Diener et al., 2010). Participants responded to eight items on a seven-point Likert scale ranging from 1 (Strongly Disagree) to 7 (Strongly Agree). Example items included: "I lead a purposeful and meaningful life," "My social relationships are supportive and rewarding," and "I am optimistic about my future." All items were summed to provide a total score ranging from 8 to 56. Internal consistency (Cronbach's α) for the eight items was 0.89.

Self-Esteem

Self-esteem was measured using a modified version of the Rosenberg Self-Esteem Scale (Rosenberg, 1965). This measure has demonstrated strong psychometric properties when administered to adolescents (Rosenberg, 1965). Participants responded to five items on a four-point scale ranging from 1 (Strongly Disagree) to 4 (Strongly Agree). Only the items associated with positive feelings toward the self were included: "On the whole, I am satisfied with myself," "I feel that I have a number of good qualities," "I am able to do things as well as most other people," "I feel that I'm a person of worth, at least on an equal plane with others," and "I take a positive attitude toward myself." All items were summed to provide an overall score ranging from 5 to 20. Internal consistency (Cronbach's α) for the five items was 0.88.

Resiliency

Resiliency was measured using two items from the Canadian Campus Wellbeing Survey (Faulkner et al., 2019). Participants responded to each item on a five-point scale ranging from 1 (Poor) to 5 (Excellent). The items followed the stem statement: "In general, how would you rate...": (a) "your ability to handle unexpected and difficult problems (a family or performance crisis)," and (b) "your ability to handle day-to-day demands in your life (work, family responsibilities)." A mean scale score was computed. The inter-item correlation (Pearson's r) for the two items was 0.72.

Data Analysis

Descriptive statistics and frequencies were computed for each variable and distributions were examined for normality. Participants with missing data for the variables of interest and covariates were removed, as were cases with unrealistic responses (i.e., average daily time use spent in movement behaviors exceeding 24 h). Isotemporal substitution modeling requires an approximate linear association between predictor variables and outcomes; and therefore, we examined whether significant quadratic relationships existed given that previous work has found non-linear associations between sleep and indicators of mental health (Gilchrist et al., 2021). Our primary analysis consisted of using two different regression models to examine relationships between movement behaviors and indicators of mental wellbeing: (1) single activity, and (2) isotemporal substitution.

First, we computed a series of single activity models to investigate independent associations between each movement behavior (i.e., MVPA, screen time, sleep) and the three indicators of mental wellbeing. Single activity models were expressed as follows:

$$\textbf{Mental wellbeing} = (\boldsymbol{\beta}\textbf{1})\ \textbf{MVPA} + (\boldsymbol{\beta}\ \textbf{2})\ \textbf{covariates}.$$

Next, a series of isotemporal substitution models were computed to examine the effects of reallocating time between MVPA, screen time and sleep on indicators of mental wellbeing. Isotemporal substitution models estimate the effects of replacing time spent engaging in one behavior with another behavior for the same amount of time (Mekary et al., 2009). By replacing a reduction in time spent engaging in one behavior with an equivalent amount of time in another behavior, total time is held constant in the equation, and the potential to create a day longer than 24 h is eliminated. Given that individuals generally spend the least amount of their day engaging in MVPA, we modeled the impact of replacing 60 min of time use in one movement behavior with another activity to represent the effects of going from being inactive (i.e., 0 min of daily MVPA) to meeting the guideline recommendation of 60 min of MVPA per day, and vice versa. Using the reallocation of MVPA to screen time or sleep as an example, the isotemporal substitution models were expressed as follows, in which the coefficients β1 and β2 express the revised estimate for mental wellbeing associated with a 60 min increase in the values for screen time and sleep at the expense of MVPA, respectively, whereas the coefficient β3 (total time), which holds time constant in the equation, represents the revised estimate for mental wellbeing associated with the activity that was replaced (i.e., MVPA):

$$\textbf{Mental wellbeing} = (\boldsymbol{\beta}\textbf{1})\ \textbf{screen time} + (\boldsymbol{\beta}\textbf{2})\ \textbf{sleep} + (\boldsymbol{\beta}\textbf{3})\textbf{total time} + (\boldsymbol{\beta}\textbf{4})\ \textbf{covariates}$$

Multilevel modeling was used to account for the nested structure of the data (i.e., participants within schools). Prior to conducting our analyses, all relevant assumptions (i.e., linearity, homogeneity, normality) were tested. Assumptions for linearity and homogeneity were met, however, the normal probability plots of residuals had considerable outliers and were not normally distributed. Mahalanobis tests indicated there were 68, 67, and 54 multivariate outliers for flourishing, self-esteem and resiliency, respectively. Since ordinary least squares regression estimates are sensitive to outliers and highly influential observations, robust regression was employed to reduce the influence of these observations. This approach decreases the weights of observations with large residuals to reduce their influence on model estimates. For our robust estimates, we used a smoothed Huber function with the tuning parameter set at $k = 1.345$ and $s = 10$ to ensure our models achieved 95% efficiency relative to the ordinary least squares estimates (Koller, 2016). Each model included gender, socioeconomic status, and race/ethnicity as covariates. Parameter estimates (β) and standard errors (SE) are reported for the single activity, and isotemporal substitution models. All analyses were performed in R (Version 4.0.3) and R Studio (Version 1.3.1093) using the *psych* (Revelle, 2011), *lme4* (Bates et al., 2015), and *robustlmm* packages (Koller, 2016). Example R-code for the analysis can be found in the **Supplementary Material**. Statistical significance was set at $p < 0.01$, which, for robust estimates, corresponds with z-values ≥ 2.58.

RESULTS

Descriptive statistics for the sample are presented in **Table 1**. The sample was on average 16 years of age and comprised of slightly more females than males. The majority of participants identified as White, and most participants lived in a household with a parent who graduated from college or university. With the exception of the relationship between sleep and flourishing, we failed to observe evidence of significant quadratic relationships between each movement behavior and the indicators of mental wellbeing. To assess the non-linear association between sleep and flourishing, we stratified our analyses for flourishing based on whether participants met the lower bound age-associated sleep threshold recommendation for youth (≥8 h of sleep each night; n = 284) or not (<8 h of sleep each night; n = 834). (1) Analyses for self-esteem and resiliency are non-stratified.

Single and Isotemporal Substitution Models

Two different models were computed to examine associations between time use in different movement behaviors (including reallocation) and three indicators of mental wellbeing among adolescents (**Table 2**).

Single Activity Models

Sleep duration and MVPA were positively associated with both self-esteem and resiliency, whereas a negative association was observed for screen time. Similar results were also found for flourishing among the subsample of participants getting less than 8 h of sleep. Comparatively, no significant associations were observed between each movement behavior and flourishing for the subsample getting at least 8 h of sleep.

Isotemporal Substitution Models

Reallocating 60 min of daily screen time to MVPA or sleep was associated with significantly better self-esteem and resiliency. Alternatively, there were no changes in self-esteem and resiliency when sleep was replaced with MVPA (and vice versa). For flourishing, significant benefits were observed when replacing screen time with MVPA. When screen time was replaced with sleep, the beneficial effects on flourishing were only observed for the subsample averaging less than 8 h of sleep. When sleep was reallocated to MVPA, no differences were observed for flourishing among the subsample averaging less than 8 h of sleep,

TABLE 1 | Demographic characteristics (N = 1,118).

	Total sample *n* (%) or *M* (SD)
Age	15.92 (0.49)
Gender (male)	509 (45.5)
Race/Ethnicity	
White	589 (52.7)
Indigenous	22 (2.0)
Black	91 (8.1)
Asian	66 (5.9)
Middle Eastern/Arab	105 (9.3)
Latin	4.5 (50)
Other	195 (17.4)
Highest parental education	
Some secondary	139 (12.4)
Completed secondary	85 (7.6)
Some post-secondary	118 (10.6)
Completed post-secondary	776 (69.4)
Moderate-to-vigorous physical activity (hours/day)	1.36 (0.98)
Screen time (hours/day)	4.68 (3.17)
Sleep duration (hours/day)	7.29 (1.40)

TABLE 2 | Single and isotemporal substitution models predicting indicators of mental wellbeing.

	Replacement activity		
	MVPA B (SE)	Sleep B (SE)	Screen B (SE)
Flourishing (≥8 h of sleep)			
Isotemporal substitution			
MVPA	–	**−1.64 (0.59)**	**−1.22 (0.45)**
Sleep	**1.65 (0.59)**	–	0.42 (0.38)
Screen time	**1.23 (0.45)**	−0.42 (0.38)	–
Single activity	0.90 (0.41)	−0.54 (0.34)	−0.15 (0.15)
Flourishing (<8 h of sleep)			
Isotemporal substitution			
MVPA	–	0.05 (0.37)	**−2.02 (0.27)**
Sleep	−0.05 (0.37)	–	**−2.07 (0.26)**
Screen time	**2.02 (0.27)**	**2.07 (0.26)**	–
Single activity	**1.95 (0.28)**	**2.03 (0.26)**	**−0.35 (0.08)**
Self-esteem			
Isotemporal substitution			
MVPA	–	0.05 (0.11)	**−0.48 (0.09)**
Sleep	−0.05 (0.11)	–	**−0.53 (0.06)**
Screen time	**0.48 (0.09)**	**0.53 (0.06)**	–
Single activity	**0.45 (0.09)**	**0.49 (0.06)**	**−0.10 (0.03)**
Resiliency			
Isotemporal substitution			
MVPA	–	−0.08 (0.03)	**−0.16 (0.03)**
Sleep	0.08 (0.03)	–	**−0.08 (0.02)**
Screen	**0.16 (0.03)**	**0.08 (0.02)**	–
Single activity	**0.16 (0.03)**	**0.08 (0.02)**	**−0.02 (0.01)**

Estimates are unstandardized. SE, standard error. All models are adjusted for sex, race/ethnicity, and socioeconomic status. Significant findings are bolded (p < 0.01).

but resulted in significantly better flourishing scores among the subsample averaging at least 8 h of sleep each night. Interestingly, for adolescents averaging more than 8 h of sleep per night, the reallocation of time spent sleeping to screen time had no effect on flourishing.

DISCUSSION

The present study examined the impact of reallocating time spent engaging in different movement behaviors on indicators of mental wellbeing among a sample of Canadian adolescents. These results generally suggest that replacing 60 min of screen time with either sleep or MVPA confers beneficial effects for flourishing, self-esteem and resiliency. Replacing sleep with MVPA (and vice versa), however, appears to have a negligible effect on self-esteem and resiliency. Getting additional MVPA at the expense of sleep or screen time appears to provide the greatest benefits for flourishing among adolescents getting sufficient sleep, whereas replacing screen time with MVPA or sleep is associated with similar benefits among adolescents achieving insufficient amounts of sleep. Collectively, findings have important public health implications, particularly regarding how health promotion campaigns frame the detrimental impact for mental wellbeing of spending time using screens at the expense of being active or resting.

Emerging research is beginning to establish how varying combinations of daily MVPA, sleep and sedentary behaviors interact to influence the mental health and wellbeing of adolescents (Sampasa-Kanyinga et al., 2020). The present study builds on the limited literature, demonstrating that replacing screen time with either MVPA or sleep is associated with higher levels of not only flourishing (Gilchrist et al., 2021), but also other important indicators of mental wellbeing that have been shown to confer protective effects against stress and the development of mental health problems. These findings are important considering recent work using a rigorous multiverse analysis has suggested that screen time alone may not be worth targeting from a policy level standpoint when attempting to improve the mental wellbeing of adolescents (Orben and Przybylski, 2019). In light of the 24-h movement paradigm, however, the true benefits may lie in the replacement of screen time with healthier alternatives (i.e., MVPA, sleep) that are known to have a positive impact on mental wellbeing. Our findings, therefore, underscore the need for intervention efforts aiming to relocate some time away from sedentary pursuits to increase the proportion of an adolescent's day that is allocated to time spent engaging in MVPA or sleep. Evidence indicates that a health promotion campaign focused on getting adolescents to turn off their screens earlier in the evening and get to sleep at a more reasonable time may hold promise for promoting their mental wellbeing (Woods and Scott, 2016).

Although we observed a quadratic relationship between sleep and flourishing that was consistent with findings of Gilchrist et al. (2021), self-esteem and resiliency both displayed linear relationships with sleep and were therefore not stratified based on sleep duration as per our hypotheses. The results for both of these indicators of mental wellbeing would suggest that replacing screen time with either sleep or MVPA confers beneficial effects of similar magnitudes. Considering the average amount of time we found adolescents spend using screens on a daily basis was more than double the recommended 2 h threshold and roughly three-quarters of the sample averaged less than 8 h of sleep each night, there appears to be ample opportunity to enhance wellbeing through replacement of time on screens with sleep later in the evening. Moreover, the relative equivalence in beta coefficients for replacing screen time with MVPA and sleep means that adolescents that potentially find MVPA aversive can still stand to improve their wellbeing simply through increasing their sleep duration. However, while focusing on replacing screen time with sleep may lead to improvements in mental wellbeing, failing to take an integrative approach that also considers MVPA could come at the expense of improvements in indices of physical health such as adiposity and cardiometabolic biomarkers (Grgic et al., 2018; Janssen et al., 2020). As more research emerges, we will gain a better understanding of how time spent amongst different movement behaviors can be best allocated to optimize a broad range of health outcomes, collectively.

Consistent with our hypotheses based on previous research (Gilchrist et al., 2021), the relationship between sleep and flourishing was best characterized as quadratic rather than linear, which led us to stratify our analyses for flourishing based on whether participants met the lower bound of the 24-h movement guideline recommendations for sleep [i.e., averaging 8 h of sleep each night (1)]. Our results for flourishing align with Gilchrist et al. (2021) in that the direction and magnitude of the observed associations for reallocating time amongst movement behaviors were predicated based on sleep duration. For the subsample of participants getting less than 8 h of sleep each night – which represents ∼75% of the sample – the pattern of results was equivalent to what was found for self-esteem and resiliency. In contrast, when adolescents met the sleep guidelines, they can stand to engage in more screen time at the expense of sleep without sacrificing their mental wellbeing, and replacing sleep with MVPA can even lead to beneficial effects for flourishing. Although replacing screen time with MVPA was positively associated with flourishing for both groups, it is worth noting that the magnitude of the effect was greater for the group not meeting current sleep guidelines. These results ultimately suggest that flourishing is more stable in adolescents who meet the sleep guidelines, and thus may provide a stronger buffer against time spent using screens instead of being active.

As depression and other mental health problems become a larger public health concern (World Health Organization [WHO], 2017), it is imperative that we identify low-cost strategies to combat these issues when they begin to manifest. Our findings indicate that health promotion strategies targeting the replacement of recreational screen time with healthy alternatives such as MVPA and sleep can benefit adolescent's mental wellbeing. Such efforts may in turn buffer against the high levels of stress and onset of mental health problems experienced during this key developmental stage. These results provide further support for the global shift toward adopting a multi-faceted approach to healthy development through targeting MVPA, sedentary behaviors and sleep concurrently. Health promotion campaigns and behavior change interventions targeted and tailored to subgroups engaging in suboptimal movement behavior patterns could represent effective means for improving population mental health from a young age (Fisher, 2021). In fact, two recent studies employing latent profile analysis have shown that adolescents classified into groups characterized by the least healthy combination of movement behaviors (i.e., low MVPA, high screen time) report the poorest scores across several indicators of mental health and wellbeing (Brown et al., 2021a,b). Evidently, this is an ideal subsample of the adolescent population to target with interventions focused on reallocating screen time to other movement behaviors. Optimal strategies by which this can be accomplished are currently unknown, but future research in this area is clearly warranted.

There are, however, limitations to this study that should be noted. First, this study was cross-sectional and only used data from the first wave of the ADAPT study, and therefore causal links cannot be inferred. As future waves of data are collected from the ADAPT study cohort, we will be able to use longitudinal modeling to establish causal links. Researchers with access to longitudinal datasets that include measures of movement behaviors and mental wellbeing are encouraged to begin exploring these links. Second, movement behaviors were assessed using self-reported measures which can introduce response bias. Third, the measures used to assess MVPA and screen time do not provide domain-specific information which may have differential effects on adolescent wellbeing. For example, meta-analytic evidence has established significant positive associations between leisure-time physical activity and wellbeing, whereas the associations with other domains of physical activity (e.g., school sport, physical education, occupational) are less conclusive (White et al., 2017). Examining specific types of physical activity and screen time in future studies may provide important information to guide precision medicine interventions. A fourth limitation relates to treating time use spent engaging in movement behaviors as absolute (i.e., hours/day) as opposed to relative (i.e., proportion of the 24-h window). Some researchers have suggested that isotemporal substitution modeling of time use data is best suited for compositional data analysis techniques given that time spent engaging in different behaviors is codependent and bounded to the 24-h period (Dumuid et al., 2019), whereas others have argued that the traditional method using absolute values provides equivalent results that may even be easier to understand given that the 24-h movement guidelines provide absolute rather than relative time-based recommendations (Mekary and Ding, 2019). Regardless of the isotemporal substitution method employed, a shortcoming of this technique is that more time can be reallocated away from a behavior than the amount reported/measured due to the hypothetical nature of these models, and thus, precision of the estimates may be biased. Nevertheless, the traditional isotemporal substitution model was considered to be more appropriate in this case as time spent engaging in MVPA and screen time may not be codependent (e.g., using the treadmill while watching TV) as would be expected when using accelerometry which captures movement behaviors purely based on intensity of motion (i.e., sleep, sedentary behavior, light physical activity, MVPA).

In conclusion, we found that substituting an hour of daily time use spent using screens with MVPA or sleep can lead to improvements in adolescent mental wellbeing. While the reallocations of MVPA with sleep (and vice versa) generally had limited impact, adolescents who meet the sleep guidelines may experience additional benefits for their self-perceived success by sacrificing an hour of sleep for MVPA. Together, findings from this research highlight the need for future health promotion campaigns and interventions adopting the 24-h movement paradigm to focus on reallocating screen time use to healthier pursuits that adolescents enjoy engaging in most.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

This study involved human participants and was reviewed and approved by the McMaster Research Ethics Board and the Hamilton-Wentworth Catholic District School Board Ethics Committee. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

DB: conceptualization, data curation, methodology, writing – original draft, and formal analysis. MK: writing – original draft, supervision, funding acquisition, and investigation. Both authors contributed to the article and approved the submitted version.

FUNDING

The ADAPT study was funded by an Insight Grant (Grant #435-2018-0896) from the Social Sciences and Humanities Research Council of Canada. MK was partially supported by a Government of Ontario Early Researcher Award.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnbeh.2021.736587/full#supplementary-material

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frontiers in Behavioral Neuroscience

ORIGINAL RESEARCH
published: 04 November 2021
doi: 10.3389/fnbeh.2021.747733

The Potential Advantages of Tai Chi Chuan in Promoting Inhibitory Control and Spontaneous Neural Activity in Young Adults

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Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to
Emotion Regulation and Processing,
a section of the journal
Frontiers in Behavioral Neuroscience

Received: 26 July 2021
Accepted: 06 October 2021
Published: 04 November 2021

Citation:
Shen Q-Q, Yin H-C, Cui L, Zhang J-Y, Wang D-L, Zhu L-N, Wang Y and Li X-J (2021) The Potential Advantages of Tai Chi Chuan in Promoting Inhibitory Control and Spontaneous Neural Activity in Young Adults.
Front. Behav. Neurosci. 15:747733.
doi: 10.3389/fnbeh.2021.747733

Tai Chi Chuan (TCC) is assumed to exert beneficial effects on functional brain activity and cognitive function in elders. Until now, empirical evidence of TCC induced intra-regional spontaneous neural activity and inhibitory control remains inconclusive. Whether the effect of TCC is better than that of other aerobic exercises is still unknown, and the role of TCC in younger adults is not yet fully understood. Here we used resting-state functional MRI (fMRI) to investigate the effects of 8-week TCC (n = 12) and brisk walking (BW, n = 12) on inhibitory control and fractional amplitude of low-frequency fluctuations (fALFF). The results found that TCC had significant effects on inhibitory control performance and spontaneous neural activity that were associated with significantly increased fALFF in the left medial superior frontal gyrus (*Cohen's d* = 1.533) and the right fusiform gyrus (*Cohen's d* = 1.436) and decreased fALFF in the right dorsolateral superior frontal gyrus (*Cohen's d* = 1.405) and the right paracentral lobule (*Cohen's d* = 1.132).TCC exhibited stronger effects on spontaneous neural activity than the BW condition, as reflected in significantly increased fALFF in the left medial superior frontal gyrus (*Cohen's d* = 0.862). There was a significant positive correlation between the increase in fALFF in the left medial superior frontal gyrus and the enhancement in inhibitory control performance. The change in fALFF in the left medial superior frontal gyrus was able to explain the change in inhibitory control performance induced by TCC. In conclusion, our results indicated that 8 weeks of TCC intervention could improve processing efficiency related to inhibitory control and alter spontaneous neural activity in young adults, and TCC had potential advantages over BW intervention for optimizing spontaneous neural activity.

Keywords: Tai Chi Chuan, exercise intervention, spontaneous neural activity, brain plasticity, functional magnetic resonance imaging, inhibition control

INTRODUCTION

Inhibition is a cognitive control process that allows us to suppress dominant and automatic responses to goal-irrelevant stimuli when needed (Nigg, 2000). It plays significant and intricate roles in different dimensions of thinking and behavioral processes, including attention (Gardner and Long, 1962), emotional perception (Ozonoff et al., 1991), and emotional regulation (Pessoa, 2009; Hendricks and Buchanan, 2016). Intervention studies have demonstrated the plasticity of inhibition function. Over the years, substantial evidence has suggested that physical exercise, an inexpensive and relatively safe intervention, is an effective method for enhancing inhibitory control. Prior studies have reported substantial exercise effects on tasks that measure inhibitory control (Tomporowski et al., 2008; van Uffelen et al., 2008; Smith et al., 2010; Chaddock et al., 2012; Verburgh et al., 2014; Tang et al., 2017; Li et al., 2020; Song et al., 2020) with increased task-related brain activation (Krafft et al., 2014; e.g., dorsolateral prefrontal cortex, medial frontal gyrus, superior frontal gyrus, middle frontal gyrus, superior temporal gyrus, cingulate gyrus, and insula). However, even in the absence of any clear sensory input or behavioral output, the brain remains active (Fox and Raichle, 2007). Spontaneous fluctuations of the blood oxygen level-dependent (BOLD) signals in functional magnetic resonance imaging (fMRI) are important manifestations of spontaneous neural activity. Recently, an increasing number of studies have used resting-state fMRI to explore spontaneous neural activity (Amad et al., 2017; Flodin et al., 2017). Furthermore, motor learning and exercise interventions have been found to induce neural plasticity in the resting brain (Wayne and Fuerst, 2013).

Tai Chi Chuan (TCC), an Asian mindfulness exercise for integrating body and mind (Wayne and Fuerst, 2013), has been shown to improve cognitive functions, such as memory and attention (Chan et al., 2008; Tao et al., 2017c). In addition, resting-state fMRI methods, like voxel-mirrored homotopic connectivity (VMHC; Chen et al., 2020), regional homogeneity (ReHo; Wei et al., 2014), and resting-state functional connectivity (rsFC; Tao et al., 2017a), have confirmed that TCC can alter spontaneous neural activity in elderly individuals. Most of these studies have described the critical functional connectivity or functional integration between different brain areas related to cognitive functions, but they couldn't provide direct information on the amplitude of brain activity in each brain region. Spontaneous low-frequency (0.01–0.08 Hz) fluctuations (LFF) have been linked to spontaneous neural activity in a region. LFF closely resembles the task-dependent activation pattern in fMRI (Biswal et al., 1995), thus providing valuable characteristic information of the spontaneous neural activity (Goldman et al., 2002; Lu et al., 2007; Mantini et al., 2007). The amplitude of the LFF (ALFF) has been used as a reliable and sensitive indicator of spontaneous neural activities in many studies (Guo et al., 2013). It has also been shown that resting-state ALFF could be used as the marker for intervention-induced neural plasticity in elderly subjects (Yin et al., 2014). However, the ALFF method is also sensitive to physiological noise. Zou et al. (2008) have proposed a fractional ALFF (fALFF) approach, which determines the ratio of the low-frequency power spectrum to that of the entire frequency range to avoid the background effects of physiological noise. Studies have revealed that correlation analysis between the fALFF and behavioral characteristics could be valuable gauges for examining the potential neural activity underlying cognitive control (Mennes et al., 2011; Deng et al., 2016). Recently, several studies have explored the effect of TCC on fALFF in older adults. Tao et al. (2017b) found that TCC and Baduanjin (popular mind-body practices) interventions can modulate medial prefrontal cortex (mPFC) fALFF and promote memory function and a significant correlation between mPFC fALFF changes and memory. Wei et al. (2017) have demonstrated that TCC practitioners have lower fALFF in the left-lateralized frontoparietal region than that in the controls (those with no regular TCC practice). However, the group difference in inhibitory control was not significant. In fact, the changes in spontaneous brain activity in older adults who practiced Tai Chi for a long period of time were not related to the performance of inhibitory control tasks. What about young adults? Since the causal relationship could not be established in a cross-sectional study, the potential role of TCC-induced intra-regional spontaneous neural activity on inhibitory control is still unknown. Besides, whether TCC, a mind-body exercise that includes mindfulness, has a different effect on inhibitory control and spontaneous neural activity from general aerobic exercise (non-mindfulness) is also worth further discussion, and the role of TCC in younger adults is not fully understood.

Therefore, the present study aimed to determine the potential advantages of TCC for promoting inhibitory control and modulating spontaneous neural activity in young adults. We hypothesized that: (1) a long-term TCC intervention could induce changes in the inhibitory control and fALFF in the brain; (2) the effect of TCC might be stronger than that of other aerobic exercises (brisk walking); and (3) inhibitory control changes induced by TCC might be associated with changes in fALFF.

MATERIALS AND METHODS

Participants and Study Design

The institutional review board of the National Key Laboratory of Cognitive Neuroscience and Learning approved the experimental procedures. All procedures were conducted in compliance with the Declaration of Helsinki. Forty-two college students were recruited by advertisement, of which six were excluded because either they had metal implants in their body or were in the abnormal range of depression scale or did not fit with the timing of the exercise intervention. Thirty-six healthy young adults without regular exercise habits were randomly divided into three groups matched by sex, namely the TCC intervention group, the BW group, and the control group. Participants were assessed by the resting-state fMRI scan and inhibitory control test before and after the 8-week intervention period. All participants provided written informed consent and were compensated for their participation. All participants completed the experiment.

Exercise Intervention Procedures

The exercise group participated in three weekly sessions for group training for 8 weeks in gym (Cui et al., 2019). The TCC group received Bafa Wubu of Tai Chi exercise. Bafa Wubu of Tai Chi has been systematically refined and organized by the General Administration of Sports of China based on the existing 24-form Tai Chi consisting of a set of Tai Chi routines popularly characterized by culture, fitness, and simplicity (Flodin et al., 2017). The first 1–3 week is the stage for "Building Xing," when the subject will master all the movements skillfully. The next 4–6 weeks are for "Conveying Qi," which focuses on the respiration of the subject during the intervention. And the final 7–8 week is mainly the stage of "using Yi," which emphasizes use mind to guide the movements and finally achieves the harmony of Xing, Qi, and Yi. The BW group received three weekly sessions for group training of BW exercise in gym (open space). Each training session (TCC and BW) lasted 60 min, starting with a 5 min warming-up and ending with a 5 min cooling-down. The polar watch (PolarElectro Oy, Kempele, Finland) was used to monitor participants' heart rates during the exercise sessions to ensure moderate exercise intensity (64% to 76% HRmax). The control group routinely maintained their original daily and physical activity habits and was instructed not to engage in any additional exercises.

Data Acquisition

Inhibitory Control Assessment

For each participant, we applied a modified flanker task to measure inhibitory control before and after the intervention period. The main aspect assessed in the flanker task is interference control at an attention level, which requires suppressing distracting stimuli and competing for response tendencies (Van den Bussche et al., 2020). Each measurement was performed after the resting-state fMRI scan outside the scanner and collected with E-prime software[1].

The stimuli were comprised of two conditions (Uono et al., 2017; Hintz et al., 2020): congruent and incongruent. Each condition was presented in 60 trials, for a total of 120 trials. Under congruent conditions, the distractor arrows were pointed in the same direction as the target arrow (<<<<< and >>>>>), while under incongruent conditions, the arrows pointed in opposite directions (<<><< and >><>>). During each trial, the participants first saw a fixation cross for 500 ms, and then the target stimulus was presented for 1,000 ms (Zhu et al., 2021). Participants were asked to respond as quickly and accurately as possible by pressing the button according to the direction of a centrally presented arrow that appeared on the computer screen and were asked to perform 12 practice trials and then complete two blocks of 60 trials each. The congruent and incongruent trials were presented in random order with equal probability in each block. Flanker accuracy was evaluated using mean accuracy, and speed was evaluated using mean Response Time (RT). The performance indicator (mean RT to incongruent trials minus mean RT to congruent trials) was used to measure reflected the ability to inhibit task-irrelevant distractor information (Hintz et al., 2020).

To minimize the learning effects, the participants performed a training task before the first study day, and the participants were asked to complete a training test until they reached 85% accuracy on the practiced flanker test.

MRI Data Acquisition

For each participant, we obtained an 8 min resting-state fMRI scan before and after the 8-week intervention period. All participants were asked to refrain from intense physical activity, caffeine, and alcohol consumption for 24 h before the day of testing. Data were acquired using a 3.0T MRI system (Siemens Magnetom Prisma; Erlangen, Germany) with a 64-channel head coil, which was located in the Beijing Normal University Imaging Center for Brain Research. Functional images were acquired using an echo-planar sequence sensitive to blood oxygenation level-dependent contrast (Xu et al., 2016; Cui et al., 2019, 2021): TR = 2,000 ms, TE = 30 ms; FA = 90°, slice thickness = 3.5 mm, 33 axial slices, voxel size = 3.5 × 3.5 × 3.5 mm, FOV = 224 × 224 mm, 240 volumes. The participants were instructed to keep their eyes open without falling asleep and to move as little as possible. As assessed by a questionnaire, none of the subjects reported falling asleep during the scanning or being uncomfortable during or after the procedure. A high resolution three-dimensional T1-weighted magnetization-prepared rapid gradient-echo images were acquired (Grewe et al., 2015; Wei et al., 2017): TR = 2,530 ms, TE = 2.98 ms, inversion time = 1,100 ms, FA = 7°, slice thickness = 1 mm, 192 sagittal slices, voxel size = 0.5 × 0.5 × 1 mm, FOV = 224 × 256 mm.

Data Analysis

Inhibitory Control Analysis

Behavioral analysis was performed using SPSS (International Business Machines Corp., NY, USA). Repeated-measures ANOVA was first conducted to explore changes in task performance in the TCC, BW, and control groups from pre-intervention to post-intervention. When the interaction effect was significant, the *post hoc* test was subsequently analyzed. For multiple comparisons of changes (post minus pre-test) of each dependent variable, the one-way ANOVA test followed by the Bonferroni *post hoc* test was used. By treating the changes in inhibitory control from before to after the exercise intervention as the dependent variable, the differences in each dependent variable among the TCC BW, and control groups were compared. All the tests were performed 2-sided, and $p \leq 0.05$ was considered significant in this analysis.

Resting-State fMRI Image Pre-processing

Functional imaging data pre-processing was implemented using GRETNA toolbox[2] based on the SPM software[3], including the following conventional steps (Zou et al., 2008; Xu et al., 2016; Cui et al., 2021): (1) discarding the first 10 time points, allowing for signal equilibrium and adaptation of the participants

[1] http://www.neurobs.com/

[2] https://www.nitrc.org/projects/gretna

[3] https://www.fil.ion.ucl.ac.uk/spm/

to the scanning noise; (2) compensating for systematic slice-dependent time shifts; (3) correcting for head movement with rigid body translation and rotation parameters; (4) normalizing into Montreal Neurological Institute (MNI) space using unified segmentation on T1-weighted images and re-slicing into 3-mm cubic voxels; (5) spatial smoothing with a 4-mm full-width at half-maximum Gaussian kernel; (6) removing the linear trend signal; and (7) regressing out nuisance variables, including head motion parameters (Friston-24), by averaging the white matter (WM) signal from the deep cerebral WM and the cerebrospinal fluid (CSF) signal-averaged from the ventricles to reduce non-neuronal contributions further. All the data used in this study satisfied the criteria for spatial movement in any direction (x, y or z) <2 mm translation or 2° rotation.

Spontaneous Neural Activity Analysis

The REST toolbox[4] (Q = rest; Qiu et al., 2018) was used to perform fALFF measurements. Following the pre-processing, the rs-fMRI time series for each voxel was transformed into the frequency domain using the fast Fourier transform. In each voxel of the brain, the fALFF was computed as the ratio between the total amplitudes across 0.01–0.08 Hz and the sum of amplitudes across the entire frequency domain (0–0.25 Hz). Then, bandpass (0.01–0.08 Hz) filtering was carried out to reduce the influence of physiological noise. For each fALFF value, we converted the normalized expression values to Z scores to eliminate the differences of whole-brain fALFF in the overall level between individuals. A 3-group (TCC, BW, and control) × 2-time (pre and post-test) repeated measures ANOVA was performed on the whole brain fALFF to obtain the brain regions with group × time significant interaction effects (FWE corrected $p \leq 0.05$ with a cluster size ≥5) using SPM. The xjView toolbox[5] was used to mask the four significant brain regions. Then, the REST toolbox was used to extract the fALFF values from the four brain regions of each subject, followed by *post hoc* statistical analysis in SPSS 25.0.

Association Between Inhibitory Control and Spontaneous Neural Activity Changes

Pearson correlation and regression analysis were used to estimate the relationship between changes in fALFF (post minus pre-test) and changes in inhibitory control (post minus pre-test) with TCC training.

RESULTS

Demographic Characteristics

Demographic characteristics are listed in **Table 1**. There were no significant differences among these three groups.

Inhibitory Control Results

For the accuracy, there were no significant main effects of group and time, and no significant interaction of group by time was found in both the congruent and incongruent conditions ($ps < 0.05$). The means and standard deviations (SD) are listed in **Table 2**.

For the inhibitory control RT, there was a significant group × time interaction ($F_{(1,33)} = 3.903$, $p = 0.03$, $\eta_p^2 = 0.191$) on the inhibitory control performance. There was no significant main effect of the group ($F_{(1,33)} = 3.903$, $p = 0.257$, $\eta_p^2 = 0.079$) or time ($F_{(1,33)} = 2.115$, $p = 0.155$, $\eta_p^2 = 0.060$) on the inhibitory control. A follow-up analysis deconstructing the interaction effects revealed that there was a significant difference between pre- and post-test in the TCC group ($F_{(1,33)} = 8.10$, $p = 0.008$, *Cohen's d* = 0.611), but no significant differences were observed between those either in the BW group ($F_{(1,33)} = 0.60$, $p = 0.443$, *Cohen's d* = 0.326) or in the control group($F_{(1,33)} = 1.22$, $p = 0.278$, *Cohen's d* = 0.376). Moreover, there was no significant difference among three groups in the pre-test ($F_{(1,33)} = 0.08$, $p = 0.928$, ($\eta_p^2 = 0.005$) but was in the post-test($F_{(1,33)} = 3.46$, $p = 0.043$, ($\eta_p^2 = 0.173$). The inhibitory control performance changes (post minus pre-test) were compared among the three groups. The results showed that inhibitory control performance was significantly improved in the TCC group compared to that in the control group ($p = 0.009$, *Cohen's d* = 1.014). The other differences did not produce any statistical significance ($ps > 0.05$; **Figure 1**).

Next, we conducted a *post hoc* power analysis using the software G*Power (version 3.1.9.7; Kiel University, Kiel, Germany) to confirm the sample sizes. We used a power analysis with Effect size $f = 0.485$ ($\eta_p^2 = 0.191$), α error of probability = 0.05, Number of groups = 3, Number of measurements = 2, and correlation = 0.554. Within our chosen total sample size, the power (1-β) was approximately 0.99.

fALFF Results

Repeated measures ANOVA on the fALFF values yielded four significant interactions (**Figure 2**): the left medial superior frontal gyrus (SFGmed.L; cluster size: 5; peak MNI coordinates: −12, 69, 9; $F = 55.33$), right dorsolateral superior frontal gyrus (SFGdor.R; cluster size: 7; peak MNI coordinates: 18, 27, 42; $F = 46.37$), right paracentral lobule (PCL.R; cluster size: 6; peak MNI coordinates: 3, −42, 60; $F = 50.56$), and right fusiform gyrus (FFG.R; cluster size: 8; peak MNI coordinates: 30, −66, −6; $F = 54.63$).

The fALFF changes (post minus pretest) were compared among the three groups. The results showed that there was a significant increase in the SFGmed.L ($p < 0.001$, *Cohen's d* = 1.533) and FFG.R ($p = 0.001$, *Cohen's d* = 1.436) and a significant decrease in the SFGdor.R ($p = 0.001$, *Cohen's d* = 1.405) and PCL.R ($p = 0.003$, *Cohen's d* = 1.132) in the TCC group compared to that of the control group. There was a significant increase in the FFG.R ($p = 0.006$, *Cohen's d* = 1.398), and the increasing trend gradually slowed down in the PCL.R ($p = 0.016$, *Cohen's d* = 1.374) and SFGdor.R ($p = 0.018$, *Cohen's d* = 0.889) in the BW group compared to that of the control group. We also found a significant increase in the SFGmed.L ($p = 0.041$, *Cohen's d* = 0.862) in the TCC group compared to that in the BW group.

Then, we conducted a *post hoc* power analysis. We used a power analysis with Effect size $f = 0.588–0.692$ ($\eta_p^2 = 0.284–0.324$), α error of probability = 0.05, Number of

[4]http://restfmri.net/forum/index.php?
[5]https://www.alivelearn.net/xjview/

TABLE 1 | Demographic characteristics.

Items	Tai Chi Chuan M (SD)	Brisk walking M (SD)	Control M (SD)	*F*	*p*
Sex (Male/Female)	2/10	2/10	2/10	—	—
Age (years)	21.83 (2.48)	21.92 (2.28)	21.75 (2.45)	0.014	0.986
Handedness (Left/Right)	0/12	0/12	0/12	—	—
Education (years)	16.33 (2.23)	16.41 (2.27)	16.33 (1.50)	0.007	0.993
BMI (kg/m^2)	20.21 (2.54)	19.15 (2.06)	21.71 (2.96)	3.07	0.06

TABLE 2 | Flanker task performance.

	Tai Chi Chuan M(SD)	Brisk walking M(SD)	Control M(SD)
Pre			
Inhibitory control RT (ms)	116.82 (16.63)	121.09 (30.36)	119.03 (31.36)
Congruent accuracy (%)	0.969 (0.040)	0.963 (0.042)	0.957 (0.037)
Incongruent accuracy (%)	0.956 (0.025)	0.962 (0.039)	0.953 (0.015)
Post			
Inhibitory control RT (ms)	95.66 (21.80)	115.32 (32.24)	127.23 (33.65)
Congruent accuracy (%)	0.967 (0.039)	0.962 (0.043)	0.953 (0.035)
Incongruent accuracy (%)	0.954 (0.021)	0.959 (0.031)	0.955 (0.015)

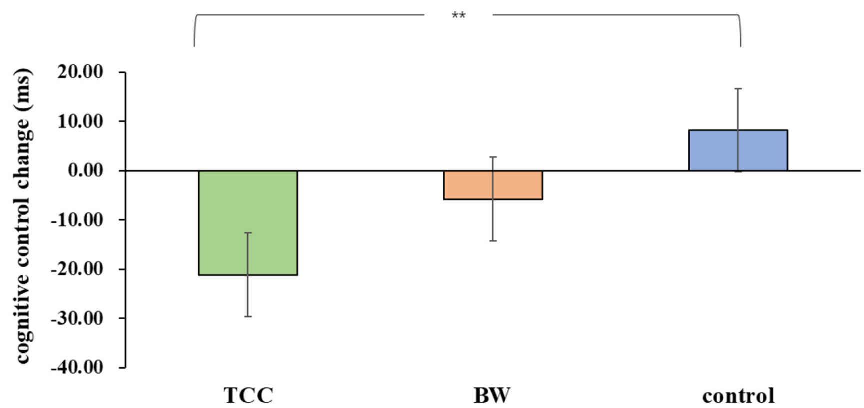

FIGURE 1 | Group differences in inhibitory control task reaction times (RT). **$p \leq 0.01$.

groups = 3, Number of measurements = 2. Within our chosen total sample size, the power (1-β) was approximately 0.99.

Association Between Inhibitory Control and Spontaneous Neural Activity Changes

Significant correlation between the SFGmed.L fALFF changes and the inhibitory control performance changes (r = 0.871, p < 0.001 significant after Bonferroni correction; **Figure 3**) was observed in the TCC group. There was no significant correlation between the fALFF changes and the inhibitory control performance changes in the BW and control groups. A linear regression analysis was performed using the inhibitory control performance changes as a dependent variable and the SFGmed.L fALFF changes as an independent variable, which showed that TCC induced fALFF changes in the SFGmed.L could explain 73.5% (adjusted R^2 = 0.735) of the observed variation in the inhibitory control performance improvement ($F_{(1,11)}$ = 31.564, β = −0.871, p < 0.001; **Table 3**).

DISCUSSION

This study aimed to examine the potential advantages of TCC for promoting inhibitory control and modulating spontaneous neural activity in young adults. To the best of our knowledge, this study was the first exercise intervention study to compare the impacts of TCC and general aerobic exercise on spontaneous neural activity and inhibitory control in young adults. We found that TCC exercise significantly increased inhibitory control performance and induced spontaneous neural activity changes. While BW exercise had no significant effect on the inhibitory control. Importantly, TCC had comparatively stronger effects on spontaneous neural activity than BW exercise, as indicated by

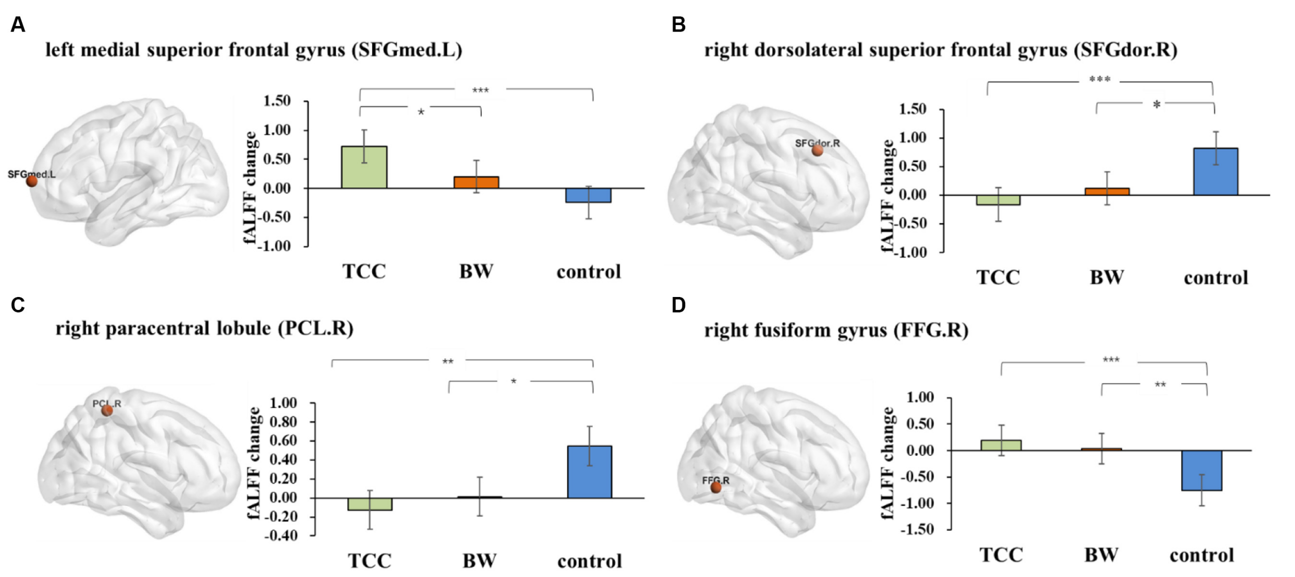

FIGURE 2 | The fractional amplitude of low-frequency fluctuations (fALFF) results. Changes in the fALFF after 8 weeks of Tai Chi Chuan (TCC) and BW. **(A)** *Post hoc* statistical analysis results of fALFF changes in the SFGmed.L-left medial superior frontal gyrus. **(B)** *Post hoc* statistical analysis of the fALFF changes in SFGdor.R-right dorsolateral superior frontal gyrus. **(C)** *Post hoc* statistical analysis results of the fALFF changes in the PCL.R-right paracentral lobule. **(D)** *Post hoc* statistical analysis results of the fALFF changes in the FFG.R-right fusiform gyrus. $^*p \leq 0.05$, $^{**}p \leq 0.01$, and $^{***}p \leq 0.001$.

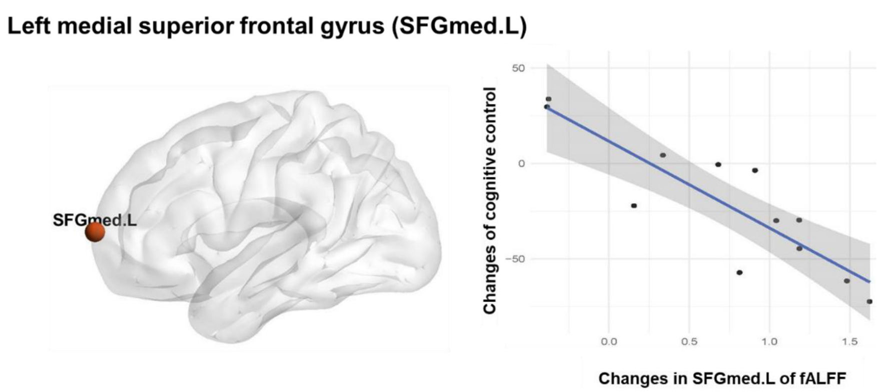

FIGURE 3 | Association between Inhibitory control and spontaneous neural activity. Pearson correlation and regression analysis of fALFF changes and inhibitory control changes in the TCC group.

TABLE 3 | fALFF changes with inhibitory control RT changes.

Independent variable	β	adjusted R^2	F	95% CI	
				Lower	Upper
SFGmed.L fALFF changes	−0.871	0.735	31.564	−63.38	−27.4

significantly increased fALFF in SFGmed.L. In addition, there was a significant positive correlation between the enhancement in inhibitory control performance and the increase in fALFF in the SFGmed.L.

Tai Chi Chuan Promoted Inhibitory Control Performance

Our findings indicated that an 8-week TCC intervention could improve inhibitory control, which was consistent with previous studies on mind-body exercise. Other studies have also found that mind-body exercises such as TCC can improve inhibitory control (Wayne et al., 2014; Zhang et al., 2018). Inhibitory control allows us to suppress dominant and automatic responses to goal-irrelevant stimuli. TCC may improve inhibitory control in the following respects.

From the perspective of movement types, TCC requires participants to abide by the basic principle of mind-body relaxation. On this basis, under the guidance of the mind, combined with breathing, the movements are correctly completed in a concentrated manner (Shaojun, 2019). During the entire movement process, individuals were asked to be intently guided by their minds and continue to be aware of their movements and respiratory rhythms so that their attention could be continuously improved (Cui et al., 2019, 2021), with better and timely modifications of the information related to inhibitory control depending on the needs of the task, which resulted in improved inhibitory control. In addition, while completing the entire set of movements, the individual was required to suppress interference by irrelevant information and suppress the prepotent responses required for corrective actions, so that the person could respond using top-to-bottom processes that involve harmonious unification and actions related to learning and memory control processes while simultaneously engaging in exercise that frequently involves inhibitory control training. Some studies have shown that the combination of physical and cognitive training may lead to a mutual enhancement of the effects of these two interventions (Hotting and Roder, 2013).

The results of this study also showed that BW exercise did not significantly improve inhibitory control. Previous studies have found that moderate-intensity aerobic exercise can improve an individual's cognitive function, which is inconsistent with the results of this study (Fox and Raichle, 2007; Song et al., 2020). This might be due to the specific nature of the research subjects, like college students, in this study. There is evidence that the influence of physical activity on cognitive functions is stronger and more obvious in teenagers and the elderly population but weaker in young adults (Voss et al., 2011). Some studies have found that movement complexity plays an important role in cognitive control (Best, 2012). Compared with TCC, BW is a relatively simple and repetitive movement with a single movement form. Our previous research on cognitive flexibility yielded similar results (Cui et al., 2021), suggesting that the improvement of cognitive function in young adults might require movement involving more cognitive operations. On the other hand, this finding may be related to the cycle of exercise, which lasted for 8 weeks in this experiment. In this study, 8 weeks of BW was found to be optimum for modulating spontaneous neural activity, which was reflected in its influence on functional brain activity, but its positive effects have not yet been shown in terms of behavior. Numerically, the inhibitory control RT of the BW group also decreased, but the decrease was not statistically significant. As a result, a longer exercise intervention time might be needed in future studies. Previous behavioral studies have shown that TCC is more beneficial to cognitive function improvement than BW in older adults (Ji et al., 2017). Thus, our study suggests that TCC may improve inhibitory control in young adults and have potential therapeutic advantages.

Tai Chi Chuan Altered Spontaneous Neural Activity

Our results showed that both TCC and BW intervention could induce spontaneous neural activity, which was consistent with the previous findings (Voss et al., 2011; Best, 2012; Ji et al., 2017; Wei et al., 2017). Both human and animal studies have shown that physical activity promotes neural plasticity in the brain, thus promoting cognitive function (van Uffelen et al., 2008; Smith et al., 2010).

The right paracentral lobule belongs to the key brain area of the motor-sensory network, which innervates motor and sensory modules of the contralateral extremities (Bruchhage et al., 2020; Deng et al., 2021). Throughout an 8-week exercise intervention, the college students gradually transitioned from the initial stage of action acquisition to the stage of action automation. Therefore, TCC decreased the spontaneous activity in the PCL.R, and brisk walking attenuated the enhancement of spontaneous activity in this brain region. The FFG.R involves facial perception (Uono et al., 2017) and body perception (Grewe et al., 2015). Both TCC and BW involve a lot of body perception in the process. For facial perception, the exercise intervention in this study was set in the form of a group, which inevitably involved facial recognition and perception, which might also be one of the reasons for improving its effects. The enhancement of fALFF in the FFG.R by TCC might be caused by the elements of mindfulness and meditation contained in the TCC (Cui et al., 2021). Furthermore, it has been found that TCC can improve levels of mindfulness (Chen et al., 2021). In the process of TCC exercise, individuals need to be guided with their own thoughts and pay more attention to the continuous awareness of movements, breathing, etc., to continuously improve the ability of mindfulness-awareness and make their sensory perception stronger. The SFGdor.R plays an important role in the process of inhibitory control. The dorsolateral prefrontal cortex is part of the executive control network, which is involved in controlling movement and cognitive tasks that require externally directed attention (Beaty et al., 2015). The SFGdor.R is located in the frontal lobe. Previous studies have also shown that functional activity changes in the cerebral cortex after physical exercise training are primarily reflected in the frontal cortex (Wei et al., 2017). Additionally, stress usually has influenced the function of mBDNF and synapse in brain (Nestler et al., 2002; Martinowich et al., 2007; Kojima et al., 2020), the unexpected changes of fALFF in the control group may be induced by participants' stress reaction during the final examination. This explanation remains speculative, as our study did not measure this pressure, so relevant analysis cannot be carried out, which can be further explored in future research.

Compared to the control group, the participants had four brain areas that displayed improved fALFF after TCC intervention and three brain areas with improved fALFF after the BW intervention. However, there was a significant difference in the SFGmed.L between the TCC and brisk walking groups. The SFGmed.L located in the mPFC, which connects the default mode network and left dorsal attention network, thus playing crucial roles in the ability of impulse control, self-awareness, regulating emotion, and attention (Qiu et al., 2011; Jiang et al., 2016; Park et al., 2018). Several studies have reported that people with schizophrenia (SZ; Cui et al., 2017), autism spectrum disorder (ASD; Yao et al., 2016), and antisocial personality disorder (ASPD; Jiang et al., 2016), and internet gaming disorder (IGD; Park et al., 2018) have abnormal activity in the SFG. TCC involves sequences moving memory and planning, inhibition of incorrect movements, etc. Compared with normal aerobic exercise, TCC practice requires more awareness, attention control, movement control, and memory components that frequently activate a participant's related functions during exercise. This finding might also be related to the learning process, and a previous study has pointed out that during the acquisition of motor skills, the brain activity shows plasticity (Halsband and Lange, 2006). TCC has more new movement forms that require participants to learn as a new experience. Physical exercise may trigger the process of promoting spontaneous neural activity in the brain, thus improving the ability of individuals to cope with new needs through behavioral adaptations, and the combination of physical training and cognitive training may lead to the mutual reinforcement of the two interventions (Hotting and Roder, 2013). TCC has both characteristics. Therefore, the effect of optimizing spontaneous neural activity in the brain is stronger, which enhances inhibitory control. Another reason might be that TCC had more advantages regarding movement forms, including mindfulness and physical training; hence the difference could be explained by mindfulness. There is a hypothesis that the frontoparietal control network is relevant for meditation and mindfulness skills (Marzetti et al., 2014). A previous review has supported this hypothesis by finding that meditation is related to the left superior temporal gyrus (Tomasino et al., 2014).

Our research showed that TCC also enhanced the fALFF in the SFGmed.L and that the enhancement of fALFF in this brain region could explain the improvements in inhibitory control induced by TCC. Several studies have supported our findings. Yin has shown that 6 weeks of TCC can enhance the ALFF in the left SFG of elderly individuals (Yin et al., 2014). A cross-sectional study has also found a relationship between inhibitory control performance and fALFF among the TCC practitioners (Wei et al., 2017), and two longitudinal studies have indicated that there is a significant change in fALFF after the TCC intervention (Tao et al., 2017b; Mei et al., 2019). But all those studies have focused on older adult populations. Since younger adults are required to use many cognitive resources to solve issues in their day-to-day lives, so it is important to explore the effect of exercise on promoting inhibitory control and spontaneous activity.

This study has several limitations. Firstly, given our small sample size, the findings should be interpreted cautiously. Secondly, the positive effect of BW on inhibitory control was not observed in this study, which might be due to insufficient exercise intervention duration. Larger sample sizes and longer exercise duration studies are warranted to confirm these results in future investigations. Thirdly, we applied a modified flanker task to measure inhibitory control, and the stimulus presentation time was 1,000 ms. However, some studies have used a shorter stimulus presentation time followed by a response window of 1,000–1,500 ms. The inconsistencies in task setting might influence the results of the relationship between inhibitory control performance and functional brain activity. Fourthly, although we comparatively strictly controlled the three groups in the same conditions except for exercise intervention, fALFF changes occurred in some brain regions in the control group. We speculate that this might be caused by the stress of final exams, but the actual causes need to be further explored in the future. Finally, the changes in other brain regions found in this study might be related to other behavioral changes caused by TCC, such as perception, meditation, and mindfulness level. The influence of TCC on these behavioral indicators warrants further analysis.

CONCLUSION

In summary, our results indicated that 8 weeks of TCC intervention could improve processing efficiency related to inhibitory control and modulate spontaneous neural activity in young adults, and TCC had potential advantages over BW intervention for optimizing spontaneous neural activity.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by National Key Laboratory of Cognitive Neuroscience and Learning. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

H-CY and LC designed the experiment. LC and Q-QS participated in the exercise intervention, collected and analyzed the data. Q-QS wrote the manuscript with substantial contributions from H-CY and LC. J-YZ, D-LW, YW, and X-JL participated in the exercise intervention. L-NZ edited the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

This study was funded by the National Key R&D Program (Grant No. 2018YFC2000600).

ACKNOWLEDGMENTS

We would like to thank Professor Shaojun Luy from the College of P. E. and Sports, Beijing Normal University, China, for his assistance with the Tai Chi (Bafa Wubu) intervention.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Behavioral Neuroscience

BRIEF RESEARCH REPORT
published: 22 November 2021
doi: 10.3389/fnbeh.2021.787688

A Brief, Individualized Exercise Program at Intensities Below the Ventilatory Threshold Exerts Therapeutic Effects for Depression: A Pilot Study

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Due to the fact that existing pharmacological treatments for depression are not ideal, effort has been devoted to the development of complementary, alternative therapies such as physical exercise. The antidepressant effect of exercise is well documented. However, current recommendations and prescriptions of exercise may be too demanding for depressed patients, as some complain about the design of exercise programs and depression is associated with reduced motivation and capacity to exercise. Therefore, appropriately designed, patient-friendly exercise programs may prove critical for the long-term maintenance and therapeutic effects of exercise. In this pilot study, we developed an exercise program based on patients' individual level of ventilatory threshold (VT), a submaximal index of aerobic capacity measured by Cardiopulmonary Exercise Testing (CPX). Compared to traditional measures, CPX provides more trustable indices of aerobic capacity and more homogenous exercise prescriptions. The main episode of the program consisted of 15–25 min of cycling twice a week at an intensity that approached but never went higher than subjects' VT (considered low to moderate in intensity). We found that in patients diagnosed with major depressive disorder or persistent depressive disorder ($n = 8$), the program resulted in a significant reduction in depressive symptoms at week 8, which was maintained at week 16. Meanwhile, patients' social functioning, quality of life, and cognitive functions improved. Although we used a single arm, non-randomized design, our results suggest that even a brief, low to moderate intensity exercise program may exert therapeutic effects for depression and CPX may be a useful tool for exercise prescriptions.

Keywords: depression, exercise, therapeutic, cardiopulmonary exercise testing (CPX), anaerobic threshold (AT)

OPEN ACCESS

Edited by:
Etsuro Ito,
Waseda University, Japan

Reviewed by:
Takashi Tarumi,
National Institute of Advanced Industrial Science and Technology (AIST), Japan
Soichi Ando,
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Specialty section:
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

Received: *01 October 2021*
Accepted: *20 October 2021*
Published: *22 November 2021*

Citation:
Sakai Y, Chen C, Toyomaki A, Hashimoto N, Kitagawa K, Inoue T, Sato A, Makihara K, Kameyama R, Wakatsuki Y, Udo N, Shirakawa R, Yokota T, Nakagawa S and Kusumi I (2021) A Brief, Individualized Exercise Program at Intensities Below the Ventilatory Threshold Exerts Therapeutic Effects for Depression: A Pilot Study. Front. Behav. Neurosci. 15:787688. doi: 10.3389/fnbeh.2021.787688

INTRODUCTION

Currently, one of the primary clinical strategies for the treatment of depression is pharmacological therapies. However, merely 60–70% of patients respond to various antidepressant treatments, while 10–30% exhibit treatment-resistant symptoms (Al-Harbi, 2012). The latter experiences substantial social and occupational difficulties, the decline of physical health, and suicidal thoughts, and have increased health care utilization. Consequently, the exploration of non-pharmacological, complementary and alternative therapies has been attracting much attention (Kessler et al., 2001). One such therapy is physical exercise (Cooney et al., 2013; Chen, 2017).

A Cochrane meta-analysis concluded that exercise led to a moderate reduction in depressive symptoms, equivalent to roughly 5 points on the Beck Depression Inventory (BDI) (Cooney et al., 2013). Typically, the exercise used is moderate to vigorous in intensity and at least three times per week. As such, the UK National Institute for Health and Clinical Excellence recommends structured exercise lasting 45 min to an hour, 3 times a week for 10–14 weeks, for the treatment of mild to moderate depression (National Institute for Health and Clinical Excellence, 2016). The Japanese Society of Mood Disorders recommends 3 sessions of exercise at moderate to vigorous intensity for the treatment of major depressive disorder (MDD) (The Japanese Society of Mood Disorders, 2016).

However, these recommended frequencies and intensities of exercise may be inadequate for depressed patients. As reported by previous studies, some patients complain about the design of the exercise programs (Blumenthal et al., 1999, 2007; Oertel-Knöchel et al., 2014). In fact, the widely prescribed frequency and intensity of exercise may be too demanding for these patients. First, depression is associated with reduced motivation to exercise (Roshanaei-Moghaddam et al., 2009; Searle et al., 2011). Second, patients with depression show reduced aerobic capacity (Martinsen et al., 1989; Sener et al., 2016) and walk slower than non-depressed people (Lemke et al., 2000).

Therefore, appropriately designed exercise programs with shorter episodes, fewer sessions and at an individualized, relatively low intensity may prove critical for the long-term maintenance of exercise in patients. But as the therapeutic effect of exercise is generally dose-dependent (Cooney et al., 2013; Chen, 2017), it is of crucial importance to specify the adequate amount of exercise that is friendly and tolerable to patients and still achieves an antidepressant effect.

Cardiopulmonary Exercise Testing (CPX) has been widely used in cardiac rehabilitation for the objective evaluation of cardiorespiratory function (Balady et al., 2010). One measure generated by CPX is the ventilatory threshold (VT), a submaximal index of aerobic capacity (Beaver et al., 1986). As the intensity of exercise increases, the oxygen requirement by the muscle becomes greater. When the oxygen requirement surpasses the oxygen supply, the body has to depend on anaerobic glycolysis for energy output, with lactate as a final metabolic byproduct. This point at which lactate accumulates faster than its rate of use in the blood is known as anaerobic threshold (AT) or lactate anaerobic threshold (LAT). The VO_2 at the onset of blood lactate accumulation is called VT or ventilatory anaerobic threshold (VAT). VT or VAT is detected using incremental exercise-induced gas exchange parameters, while AT or LAT is detected by direct metabolic measures (e.g., lactic acid). An increase in ventilation is required to eliminate the excess carbon dioxide (CO_2) produced during the conversion of lactic acid to lactate. This causes the shortness of breath and the feeling of effortful.

Exercise at an intensity below VT is perceived as less demanding. Specifically, in healthy subjects, VT usually occurs at 45–65% of maximal aerobic capacity (VO_2max) (Davis et al., 1976) and exercise at an intensity below VT is thus considered low to moderate in intensity (Swain and Franklin, 2006).

To our knowledge, to date, no study has evaluated the therapeutic effect of exercise at an intensity below VT—at low to moderate intensity—in depressed patients. Previous studies conducted in depressed patients have generally used exercise at moderate to vigorous intensity, for instance, at 50–85% of heart rate reserve (maximum heart rate minus resting heart rate) (Blumenthal et al., 1999, 2007; Penninx et al., 2002).

Furthermore, the measures employed by previous studies in evaluating the intensity of exercise training in depressed patients, such as heart rate reserve (Blumenthal et al., 1999, 2007; Penninx et al., 2002), has recently been found to be a somewhat unreliable estimate of aerobic capacity (Solheim et al., 2014). In contrast, CPX can provide more trustable indices of aerobic capacity and more homogenous exercise prescriptions (Mann et al., 2013). To date, no study has employed CPX to monitor the intensity of exercise training in depressed patients.

In this pilot study, we aimed to investigate the therapeutic effects of an exercise program developed based on patients' individual level of aerobic capacity. Specifically, employing CPX, we measured each patient's VT and asked them to exercise (cycle using an ergometry) twice a week at an intensity below their VT. We hypothesized that exercising twice a week at an intensity below VT reduces depressive symptoms in clinical patients. Furthermore, this may be accompanied by reduced anxiety symptoms and improved sleep quality, social functioning, quality of life, and cognitive functions, etc.

MATERIALS AND METHODS

Subjects

We recruited outpatients throughout the period of February to August 2017 at Hokkaido University Hospital, where the study was approved by the Institutional Review Board. The inclusion criteria were (1) being diagnosed with MDD or persistent depressive disorder (dysthymia) by a senior psychiatrist during clinical interviews according to Diagnostic and Statistical Manual of Mental Disorders (DSM)-5, (2) aged 20–60 years, and (3) being able to provide a written informed consent after being explained the details of the study. The exclusion criteria were (1) severe depression, as indicated by scoring 20 or above on the Hamilton Rating Scale for Depression (HAM-D), (2) strong suicidal thoughts, (3) high manic symptoms, as indicated by scoring 13 or above on the Young Mania Rating Scale (YMRS), (4) active inflammatory disease, (5) malignant tumors, (6) being unable to exercise due to orthopedic diseases, (7) already exercising regularly, (8) other conditions when considered inappropriate by the research director (for instance, body weight greater than the allowance of the ergometry used for exercise, see below).

Study Design and Procedures

As a pilot study, we used a single arm, non-randomized design. Subjects attended the exercise program while continued their routine pharmacological treatment. The changes in their symptoms from before to after the exercise program were used to assess the therapeutic effect of the exercise program.

The exercise program consisted of two supervised sessions per week for 16 consecutive weeks. Each session lasted 45–55 min and was conducted between 10:00 to 11:30 am. It was initialized by a 10-min stretching exercise and a 5-min warm-up cycling on an ergometry (type 75XL II, 75XL III, or 800, Combi Corporation, Tokyo, Japan). The main episode of exercise was a 15–25 min cycling at an intensity that approached but never went higher than subjects' VT. Specifically, heart rate was used to monitor the exercise intensity. If subjects' heart rate exceeded their level of heart rate at VT, the load was reduced by 5–10 watts/min and subjects' heart rate confirmed again. This process was repeated until subjects' heart rate decreased to below the level of heart rate at VT. Meanwhile, the intensity of the cycling was further moderated in a way such that subjects' perceived exertion stayed below 13 (somewhat hard) as evaluated by the Borg Rating of Perceived Exertion Scale. Each session was then finalized by a 5-min cool-down cycling followed by another 10-min stretching exercise.

Measurements

Before the start of (week 0), amid (week 8), and at the end of (week 16) the exercise program, we evaluated subjects' symptoms of depression and anxiety, sleep quality, quality of life, and social functions using the following measurements.

Depressive symptoms. HAM-D, Clinical Global Impressions-Severity Illness Scale (CGI-S), and BDI-II
Anxious symptoms. State-Trait Anxiety Inventory-JYZ (STAI)
Sleep quality. Pittsburgh Sleep Quality Index (PSQI)
Quality of life. 36-Item Short Form Health Survey® (SF-36v2)
Social functions. Social Adaptation Self-evaluation Scale (SASS)

Whereas HAM-D and CGI-S were evaluated by a structured interview, other measures were all self-assessment.

At week 0 and 16, CPX was conducted with an upright electromechanical ergometric bicycle using a ramp protocol (15–25 watts/min) to evaluate VT and VO_2max. During CPX, respiratory gas analysis was simultaneously performed with a breath-by-breath apparatus (Aeromonitor AE-310S, Minato Medical Science, Osaka, Japan). Finally, the VT was determined by the V-slope method (Beaver et al., 1986). Specifically, VT was defined as the non-linear point of increase in the slope of CO_2 production versus oxygen uptake during the incremental exercise. Body weight and height were also measured. Finally, the following tests were employed to evaluate cognitive functions.

Cognitive functions. The following tests were conducted according to our previous studies (Toyomaki et al., 2008; Shimizu et al., 2013): Continuous Performance Test (CPT), Wisconsin Card Sorting Test (WCST), Stroop Test, Trail Making Test (TMT), Word Fluency Test (WFT), and Verbal Memory Test (VMT).

Statistical Analysis

The statistical analysis was conducted with IBM SPSS Statistics 26.0. The normality of the data was checked using the Shapiro–Wilk test. Repeated-measures analysis of variance (ANOVA) or the Friedman test (when necessary) was used to assess the effect of the exercise program on depressive and anxious symptoms, sleep quality, quality of life, and social functions, with time as the within-subjects factor (week 0, 8, and 16). When necessary, a paired t-test or Wilcoxon signed-rank test was used for the *post hoc* pairwise comparison between different time points. Paired t-tests or Wilcoxon signed-rank tests (when necessary) were used to compare cognitive functions, VT, VO_2max, body weight, and height before and after the program. Effect size (Cohen's d) and *post hoc* power analysis was calculated using G*Power Version 3.1.9.7 (Faul et al., 2007). $P < 0.05$ was considered statistically significant. For analyses with *post hoc* pairwise comparisons, the Bonferroni correction was used to adjust the significance level.

RESULTS

Subject Characteristics

Among the 12 initially enrolled patients, four dropped out and 8 (66.7%) were eligible for the final analysis. Among those who dropped out, 2 experienced worsening symptoms of depression because of reasons considered irrelevant to the current exercise program, and 2 moved to another city because of work or family related issues.

The final 8 subjects had a mean age of 42.1 ± 12.7 years. 6 (75%) were females, 3 (37.5%) were married, and 1 (12.5%) being employed. 6 (75%) were diagnosed as MDD while the other 2 (25%) persistent depressive disorder. 5 of the 6 patients (83.3%) with MDD suffered from a recurrent episode.

1 subject (12.5%) had a comorbid social anxiety disorder, 1 obsessive-compulsive disorder, and 1 gender identity disorder. The approximate dose equivalent of antidepressants being administered was 139.1 ± 162.7 mg/d of imipramine. The approximate dose equivalent of anxiolytics being administered was 139.1 ± 162.7 mg/d of diazepam. The approximate dose equivalent of antidepressants and anxiolytics did not change between week 0 and 16 (both $p > 0.10$).

Intervention Effects

Compared to before the exercise program (week 0), the mean score of HAM-D significantly decreased at week 8 and maintained at the same level until week 16 (**Figure 1**). Repeated-measures ANOVA revealed a significant effect of time [$F(2,14) = 17.206$; $p = 0.000$]. *Post hoc* comparisons showed that the mean score of HAM-D at week 8 and 16 were lower compared

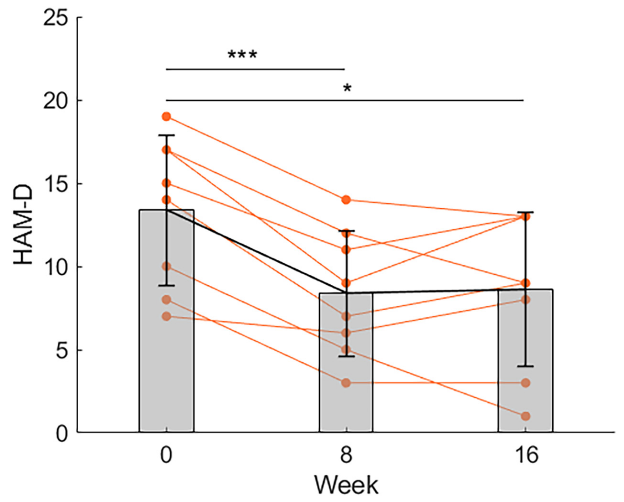

FIGURE 1 | Changes in the score of HAM-D. Compared to before the exercise program (week 0), the mean score of HAM-D significantly decreased at week 8 and maintained at the same level until week 16 (n = 8). *$p < 0.05$, ***$p < 0.001$. Data is shown as mean ± SD. Orange points represent individual data.

TABLE 1 | Outcome measure before, during, and after the exercise program.

Variables	Week 0	Week 8	Week 16
HAM-D	13.4 ± 4.2	8.4 ± 3.5***	8.6 ± 4.3*
CGI-S	3.5 ± 1.0	3.0 ± 0.5	3.0 ± 0.7
BDI-II	25.0 ± 6.6	20.0 ± 6.3	18.4 ± 6.7
State anxiety, STAI Y1	59.1 ± 6.4	54.3 ± 7.9	55.1 ± 9.2
Trait anxiety, STAI Y2	65.6 ± 7.1	59.9 ± 9.8	56.5 ± 10.9
PSQI	11.1 ± 3.3	10.8 ± 3.1	9.3 ± 4.1
SASS	25.1 ± 6.3	31.1 ± 8.0*	27.4 ± 7.7
SF-36v2: physical functioning	76.3 ± 21.4	79.4 ± 15.6	86.3 ± 20.1
SF-36v2: role physical	71.9 ± 21.9	74.2 ± 18.0	73.5 ± 24.1
SF-36v2: bodily pain	59.9 ± 26.1	65.1 ± 25.1	63.8 ± 27.8
SF-36v2: general health	34.0 ± 21.6	45.4 ± 25.3	44.5 ± 24.2
SF-36v2: vitality	29.7 ± 13.3	45.3 ± 20.0*	41.5 ± 17.9
SF-36v2: social functioning	51.6 ± 10.4	68.8 ± 24.7	73.4 ± 20.8
SF-36v2: role emotional	44.8 ± 15.1	72.9 ± 19.6*	60.4 ± 25.4
SF-36v2: mental health	37.5 ± 13.1	50.0 ± 20.8	49.4 ± 15.2
CPT: error	2.0 ± 1.7	–	1.9 ± 1.5
CPT: response time (milliseconds)	455.0 ± 34.4	–	456.9 ± 46.9
WCST: categories achieved	5.0 ± 0.9	–	5.0 ± 1.2
WCST: perseverative errors of Milner	1.5 ± 2.3	–	1.6 ± 2.1
WCST: perseverative errors of Nelson	2.0 ± 2.8	–	1.9 ± 2.1
Stroop Test: Kanji-controlled	5.4 ± 2.8	–	6.1 ± 2.4
Stroop Test: error	0.5 ± 0.9	–	0.9 ± 1.3
TMT Part A (seconds)	77.0 ± 15.0	–	68.0 ± 10.4*
TMT Part B (seconds)	94.6 ± 19.2	–	83.1 ± 17.1
WFT	26.6 ± 10.5	–	26.0 ± 8.7
VMT: immediate recall	4.6 ± 1.5	–	5.9 ± 1.5
VMT: delayed recall	7.1 ± 2.0	–	8.4 ± 1.9

**p* < 0.05, ****p* < 0.001 compared to Week 0.
Data are shown as mean ± SD.
HAM-D, Hamilton Depression Rating Scale; BDI-II, Beck Depression Inventory-II; CGI-S, Clinical Global Impressions-Severity Illness Scale; STAI, State-Trait Anxiety Inventory; PSQI, Pittsburgh Sleep Quality Index; SF-36v2, Short Form Health Survey®; SASS, Social Adaptation Self-evaluation Scale; CPT, Continuous Performance Test; WCST, Wisconsin Card Sorting Test; TMT, Trail Making Test; WFT, Word Fluency Test; VMT, Verbal Memory Test.

to that at week 0 (p = 0.0007, Bonferroni corrected, d = 2.42 and p = 0.012, Bonferroni corrected, d = 1.49, respectively), while the mean score of HAM-D at week 8 was no different from that at week 16. A *post hoc* power analysis for HAM-D scores was conducted. The *post hoc* statistical power for the change at week 8 and 16 compared to week 0 was 0.998 and 0.823, respectively, using a significance level of 0.05/3 and two-sided tests.

Furthermore, the mean score of the Vitality and the Role Emotional (RE) subscale of SF-36v2 increased at week 8 compared to week 0 (see **Table 1**). Repeated-measures ANOVA revealed a significant effect of time [$F(2,14)$ = 5.897, p = 0.014 for Vitality; $F(2,14)$ = 6.827, p = 0.009 for RE] and *post hoc* comparisons showed that the mean score at week 8 was higher compared to that at week 0 (p = 0.024, Bonferroni corrected, d = 1.30 for Vitality, p = 0.027, Bonferroni corrected, d = 1.27 for RE, respectively), while the difference between week 0 and week 16 and between week 8 and week 16 were not significant. For the mean score of SASS, the data at week 0 and 8 but not week 16 were normally distributed. We therefore conducted a paired t-test between week 0 and 8 and a Wilcoxon signed-rank test between week 0 and 16 and week 8 and 16. The results showed that the mean score of SASS at week 8 was significant higher compared to that at week 0 (p = 0.012, Bonferroni corrected, d = 1.47), while the difference between week 0 and week 16 and between week 8 and week 16 were not significant.

For the mean score of CGI-S, BDI-II, the trait anxiety subscale of STAI, and the Physical Functioning, General Health, and Mental Health subscales of SF-36v2, repeated-measures ANOVA or the Friedman test indicated a significant effect of time, but *post hoc* comparisons revealed no reliable significant difference among the three time points after Bonferroni correction (data shown in **Table 1**).

For cognitive functions, as shown in **Figure 2**, the mean time to finish TMT Part A significantly decreased at week 16 compared to week 0, as indicated by a paired t-test (p = 0.049, d = 0.84).

For all other comparisons, no significant difference was detected (data shown in **Table 1**).

DISCUSSION

Compared to previous studies which generally prescribed exercise at least 3 times a week and at an intensity of 50–85% of heart rate reserve (Blumenthal et al., 1999, 2007; Penninx et al., 2002), our program is considered at low frequency and low to moderate intensity. Nevertheless, the program resulted in a clinically significant reduction in depressive symptoms at week 8, which was maintained at week 16, as evaluated by the objective measure HAM-D.

Meanwhile, we found that, at week 8, patients' social functioning and quality of life in terms of vitality and

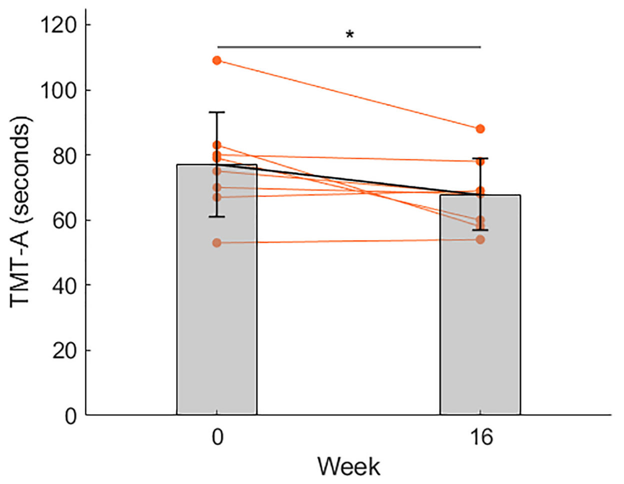

FIGURE 2 | Changes in the reaction time (seconds) of TMT-A. Compared to before the exercise program (week 0), the mean reaction time decreased at week 16. *$p < 0.05$. Data is shown as mean ± SD. Orange points represent individual data.

emotional well-being increased. At week 16, patients' cognitive functions in terms of visual search and motor processing ability improved, as indicated by reduced time to finish relevant tasks. These results suggest that our exercise program may at least partially improve patients' social and cognitive functioning and enhance their positive emotions such as vitality. These positive outcomes play a pivotal role in patients' successful rehabilitation and re-adaptation to the social world. Given that most of our patients had recurrent episodes or persistent symptoms, these results are consistent with the observation that exercise prevents the recurrence of depression (Blumenthal et al., 1999).

The dose-dependent effect of exercise in preventing and treating depression has been well-established (Cooney et al., 2013; Chen, 2017). Yet, the introduction and maintenance of high frequency, high intensity exercise in clinical settings is practically difficult. As we have mentioned earlier, depression is associated with both reduced motivation and lower capacity to exercise. Therefore, initiating an exercise program at a patient-friendly, individualized, low frequency, relatively low intensity manner and with brief episodes may be the key toward the maintenance of exercise and the achievement of therapeutic effects.

Notably, among multiple cognitive outcomes, only one test measuring visual search and motor processing ability (i.e., TMT, Part A) showed improvement after the exercise program. Other measures of higher cognitive functions such as cognitive flexibility, inhibitory control, and verbal memory remained unchanged. The underlying explanation of such results is unclear. One possibility is that given the small sample size, our study was underpowered to detect improvement in these higher cognitive functions. Nevertheless, previous studies have generally failed to identify any cognitive effects of exercise in depression (Brondino et al., 2017; Sun et al., 2018). Our study suggests the possibility that exercise at relatively low intensity is perhaps more likely to achieve cognitive-enhancing effects in depressed patients because of a higher rate of adherence (Sun et al., 2018). Future research is required to test such a possibility and clarify the underlying explanation of our findings. The primary limitation of our study is that we used a single arm, non-randomized design and thus could not exclude the potential effect of antidepressants and other factors such as the pure passage of time or repeated testing (i.e., the practice effect on TMT Part A). Our sample size was also relatively small. Future research is necessary to confirm our findings with randomized controlled trials and bigger samples.

In conclusion, our pilot study suggested that even a brief, low to moderate intensity exercise program such as 15–25 min of cycling at an intensity below VT twice a week may have therapeutic effects for patients with depression and that CPX may be a useful tool for exercise prescriptions.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Hokkaido University Hospital Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

YS, TY, and SN: study concept and design. YS, AT, KK, TI, AS, KM, RS, TY, SN, and IK: acquisition and analysis of clinical data. YS, CC, AT, NH, KK, RK, YW, NU, and SN: interpretation of clinical data. YS, NH, CC, and SN: drafting of the manuscript. All authors critical revision of the manuscript for important intellectual content.

FUNDING

This work was supported in part by JSPS KAKENHI Grant Number 16K10184.

ACKNOWLEDGMENTS

We thank all of the patients for their cooperation. We are grateful to Takayuki Nakajima, Takahiro Abe in the Department of Cardiovascular Medicine, Hokkaido University Graduate School of Medicine, and Satoshi Ikeda, associate professor in the Department of Rehabilitation Medicine, Hokkaido University Hospital for the technical support.

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BRIEF RESEARCH REPORT
published: 13 January 2022
doi: 10.3389/fnbeh.2021.802564

Self-Control and Emotion Regulation Mediate the Impact of Karate Training on Satisfaction With Life

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Physical activity is an important determinant of a healthy lifestyle. Regular participation in sports-related activities contributes to the maintenance of good psychophysiological and social health. Long-term physical activity has a positive impact on subjective well-being and can reduce stress. Karate is a specific physical activity which focuses on self-regulation and self-development; therefore, it may reduce impulsivity and improve self-control. Good self-control is also related to satisfaction with life and well-being. The presented study aimed to examine the possible intermediate impact of self-control and emotion regulation on the relationship between karate training and satisfaction with life. Fifty-eight karate practitioners and fifty-nine control subjects participated in the research. The Satisfaction With Life Scale and the Brief Self-Control Scale were applied in order to assess life satisfaction and the general level of self-control. The Emotion Regulation Questionnaire was used to assess suppression and reappraisal, both of which are distinct aspects of emotion regulation. The direct and indirect relationships between karate training and satisfaction with life were investigated using a linear regression model that included self-control, suppression and reappraisal as mediating variables. No direct effects of karate training on satisfaction with life were found, whereas karate training was indirectly associated with satisfaction with life via the indirect path that leads through self-control and reappraisal. This indicates that self-control and reappraisal fully mediate the impact of karate training on subjective well-being. Karate training can therefore play an important role in shaping volitional and personality characteristics, both of which contribute to increasing the well-being of trainees.

Keywords: self-control, emotion regulation, self-regulation, satisfaction with life, well-being, karate training, martial arts

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Edited by:
Chong Chen,
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Reviewed by:
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Specialty section:
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

Received: *26 October 2021*
Accepted: *27 December 2021*
Published: *13 January 2022*

Citation:
Potoczny W, Herzog-Krzywoszanska R and Krzywoszanski L (2022) Self-Control and Emotion Regulation Mediate the Impact of Karate Training on Satisfaction With Life. Front. Behav. Neurosci. 15:802564. doi: 10.3389/fnbeh.2021.802564

INTRODUCTION

The issue of life satisfaction has attracted researchers' attention for several decades. Despite many studies, life satisfaction remains an ambiguous concept and is a current topic of inquiry. Life satisfaction involves evaluating the quality of a person's life based on this person's own set of criteria (Pavot and Diener, 1993). Life satisfaction is a key factor in psychological and subjective well-being because it is associated with a positive attitude toward life and the absence of negative feelings (Diener, 1984). The assessment of satisfaction with one's life may concern various areas of life, such as health, interpersonal relations or financial situation, and it may be formulated in terms of the past, present and future. People combine judgments about various aspects of their lives and integrate them to assess their overall sense of life satisfaction. Generalized satisfaction with life framed in this way can be assessed quantitatively using a single-scale self-report tool (Diener et al., 1999).

Researchers are trying to determine the factors that influence satisfaction with life. Current findings indicate that health status substantially impacts life satisfaction. People who suffer from severe or chronic illnesses have significantly worse well-being and lower life satisfaction (Hutchinson et al., 2004; Strine et al., 2008). Additionally, the lower the life satisfaction, the higher the risk of obesity and health-risk behaviors, such as smoking and alcohol abuse (Strine et al., 2008).

This paper focuses on the possible impact of physical activity and karate training on satisfaction with life. Regular participation in sports training is associated with both physical and psychological components of human health. The results of a meta-analysis conducted by Eime et al. (2013) indicate that physical activity can reduce stress and has a positive impact on satisfaction with life. Other studies also report that long-term physical activity is associated with a higher subjective well-being, and more adaptive responses to negative emotions (Lechner, 2009; Downward and Rasciute, 2011; Asztalos et al., 2012).

Additionally, people who train in sports clubs have a higher level of life satisfaction compared to people who exercise individually (Eime et al., 2010). This result may be explained by the experience of social integration during training, which may enhance well-being (Vilhjalmsson and Thorlindsson, 1992; Eime et al., 2010). Other analyses also indicate that reducing levels of loneliness and fulfilling the need to belong may be significantly related to satisfaction with life (Schumaker et al., 1993; Mellor et al., 2008).

Karate training is a specific physical activity which focuses on the self-regulation and self-development of trainees (Cynarski, 2014). In karate, body training is connected with personality improvement because it focuses on self-awareness and striving to achieve development in each domain of life. Getting rid of aggression, being systematic, and focusing on the goal are principles that students learn on day 1 (Piotrkowicz, 1998). Fuller (1988) noticed that: "*the martial arts may be viewed as formalized, refined systems of human potential training which provide interesting practical models and mechanisms of psychological intervention.*" (pp. 318). This understanding of the role of martial arts indicates the possible importance of karate training for improved psychological well-being.

Both satisfaction with life and karate training are associated with self-control. Self-control can be defined as the ability to change one's behaviors or reactions and suppress unwanted impulses in order to adapt to a situation. Self-control is particularly relevant to motivational conflicts in which one must resist a pleasurable temptation in order to satisfy a long-term goal (Tangney et al., 2004; Hofmann et al., 2014). Individuals who less frequently control their reactions are considered lower in dispositional self-control (Tangney et al., 2004; Duckworth and Steinberg, 2015). Research conducted by Hofmann et al. (2014) indicates that level of self-control is a significant predictor of well-being and satisfaction with life. Karate training improves trainees' discipline and self-control (Messaoud, 2015). In their meta-analysis, Vertonghen and Theeboom (2010) analyzed 27 studies on the socio-psychological aspects of martial arts practice among adolescents. Their findings seem to support the hypothesis that training has positive effects on well-being and self-control. The analyzed studies mainly indicate that martial arts practitioners have a higher level of self-regulation and psychological well-being, and a lower level of violence. Other studies also indicate that Eastern martial arts training can directly improve trainees' self-control (Lakes and Hoyt, 2004). Karate training also effectively reduces the level of aggression and impulsiveness, both of which are negatively related to satisfaction with life (Zivin et al., 2001; MacDonald et al., 2005). This suggests that karate training may indirectly foster the attainment of a high quality of life by having a beneficial effect on self-control.

In addition to self-control, emotion regulation may also play a mediating role in the effects of karate training on life satisfaction. Emotion regulation can be defined as the processes that are responsible for monitoring, evaluating, and modifying emotional responses by initiating, inhibiting, or modulating them (Thompson, 1994; Niven et al., 2009). Gross (1998) concentrated on two common forms of emotion regulation: cognitive reappraisal and expressive suppression. Gross and John (2003) showed that cognitive reappraisal is a more adaptive strategy than suppression since it fosters well-being and interpersonal functioning.

The control of emotional reactions is also important in sports training. Research confirms that people who participate in sports activities have better self-control and use more adaptive forms of emotion regulation (Vertonghen and Theeboom, 2010; Kucharski et al., 2018); moreover, acquiring expertise in sports requires high levels of self-regulation and self-motivation (Kavussanu and Kitsantas, 2011; Kitsantas et al., 2017). Karate, like other physical activities, improves the subjective well-being and general health of participants (Bu et al., 2010; Chang and Jang, 2018), therefore it may have an impact on satisfaction with life. The presented study aimed to examine the possible intermediate impact of self-control and emotion regulation on the relationship between karate training and satisfaction with life. For this purpose, we studied a group of karate practitioners and a control group of non-training subjects. We then attempted to determine whether there are indirect effects in a mediation model in which the explanatory variable is karate training, the mediating variables are self-control and emotion regulation, and the response variable is life satisfaction.

METHOD

Subjects

The minimum sample size needed to detect the effect size of $f^2 \geq 0.15$ with probability ≥ 0.9, assuming the type I error rate set at $\alpha = 0.05$ was 108. The study was attended by 117 people selected on purpose to two groups. 58 subjects (43 males and 15 females; mean age 25.95, with standard deviation 7.37) trained karate in clubs representing different training styles (Oyama and Kyokushin) for at least 1 year (mean 8.07). Another criterion of inclusion was participation in at least one training session per week at the club under the supervision of a coach. The control group consisted of 59 non-training subjects (44 males and 15 females; mean age 26.61, with standard deviation 6.59). These people were mainly students and office workers who did not undertake any regular sports training.

Measures

Satisfaction With Life Scale

The Satisfaction With Life Scale (SWLS), developed by Diener et al. (1985) and adapted into Polish by Jankowski (2015), was used to measure the cognitive-judgmental aspect of subjective well-being. This questionnaire contains five statements (all positively worded) rated on a seven-point Likert-type scale. The summed total score on SWLS ranges from 5 to 35 points: high values reflect high levels of satisfaction with life. The high value (0.86) of Cronbach's α (Jankowski, 2015) indicates good internal consistency of the Polish version of SWLS. Test-retest reliability in 3-week intervals was 0.85–0.93; in 6-week intervals it was 0.87–0.88; in the 9-week interval, it was 0.86 (Jankowski, 2015).

Brief Self Control Scale

Pilarska and Baumaister's (2018) Polish adaptation of the Brief Self-Control Scale (BSCS) (Tangney et al., 2004) was used to measure dispositional self-control. The BSCS is a thirteen-item self-report questionnaire that consists of four positively worded statements and nine negatively worded statements. The subject is asked to rate each statement on a five-point Likert scale: from 1 ("not at all") to 5 ("very much"). The BSCS score is computed as the sum of ratings of all items after reverse coding of negatively worded items; high values reflect greater self-control. Pilarska and Baumaister (2018) confirmed that the Polish version of BSCS has good internal consistency (Cronbach alpha:0.84) and satisfactory temporal stability in a 2-week test-retest (Pearson correlation for test-retest:0.87).

Emotion Regulation Questionnaire

The Emotion Regulation Questionnaire (ERQ) (Gross and John, 2003), as translated into Polish by Kobylińska (2011) using a back translation procedure, was used to assess two aspects of emotion regulation. This questionnaire consists of ten items that form two scales: "Suppression" (four questionnaire items) and "Reappraisal" (six questionnaire items). The subject responds to each item by providing an answer on a seven-point Likert-type scale (from 1—completely disagree, to 7—completely agree). Higher scores indicate a stronger tendency to use suppression and reappraisal. The internal consistency of the questionnaire, as assessed by Cronbach's α in a study of 349 people, was 0.77 for Reappraisal and 0.74 for Suppression (Śmieja et al., 2011).

Statistical Analysis

Means with 95% confidence intervals, medians, standard deviations, and interquartile ranges were calculated to assess the location and dispersion of scores obtained in SWLS, BSCS, and ERQ. Skewness and kurtosis were used to assess the shape and normality of the distribution of scores.

Mediation analysis in a parallel multiple mediation model (MacKinnon, 2012) was conducted to examine whether self-control, suppression and reappraisal mediate the impact of Karate training on satisfaction with life. Parameter estimates for indirect, direct, and total effects were estimated using multiple linear regression fit by ordinary least squares (Hayes, 2018) and were tested for significance using bias-corrected bootstrap confidence intervals (Bollen and Stine, 1990; Shrout and Bolger, 2002; Preacher and Hayes, 2008) with 5,000 replications. Age dichotomized by median split (24 years) and gender were entered into the mediation model as covariates to control their impact on satisfaction with life. Mediation analyses were conducted in jamovi Advanced Mediation Models (jAMM) module (Gallucci, 2021). Jamovi (The jamovi project, 2021) is free and open-source statistical software which is based on the R programming language for statistical computing (R Core Team, 2021).

RESULTS

Descriptive statistics in the karate training group and the control group for scores in BSCS, ERQ, and SWLS are presented in **Table 1**.

More than half of the variance in SWLS scores, $R^2 = 0.546$, $p < 0.001$, was explained by the full regression model, which was included in the mediation analysis, which estimates the indirect,

TABLE 1 | Descriptive statistics for scores on scales of self-report measures.

Scale	Training	Mean	95% confidence interval for mean		Median	SD	IQR	Skewness		Kurtosis	
			Lower	Upper				Skewness	SE	Kurtosis	SE
BSCS	No	43.59	41.94	45.25	43	6.49	9	−0.256	0.311	−0.279	0.613
	Yes	48.12	46.19	50.05	48	7.49	11.75	−0.126	0.314	−0.686	0.618
ERQS	No	16.48	15.21	17.75	16	4.98	7.5	0.279	0.311	0.111	0.613
	Yes	16.10	14.86	17.38	16	4.97	7.25	0.055	0.314	−0.050	0.618
ERQR	No	28.12	26.60	29.64	28	5.97	7.5	−0.204	0.311	0.261	0.613
	Yes	31.31	30.02	32.60	31.5	4.50	5.75	−0.505	0.314	0.694	0.618
SWLS	No	22.39	21.59	23.19	23	3.15	3	−0.407	0.311	0.685	0.613
	Yes	24.02	23.01	25.02	24	3.91	4	−0.371	0.314	0.660	0.618

SD, standard deviation; IQR, interquartile range; SE, standard error; BSCS, Brief Self-Control Scale; ERQS, Suppression scale in Emotion Regulation Questionnaire; ERQR, Reappraisal scale in Emotion Regulation Questionnaire; SWLS, Satisfaction with Life Scale.

TABLE 2 | Fit measures and overall model tests for linear regression models included in the mediation analysis, which estimates indirect, direct and total effects of karate training on satisfaction with life, with self-control, suppression, and reappraisal as mediating variables, and with gender and dichotomized age as covariates.

					Overall model test			
Model	**Dependent variable**	**R**	**R^2**	**Adjusted R^2**	**F**	**df1**	**df2**	**p**
Mediator model	BSCS	0.490	0.240	0.220	11.89	3	113	<0.001
	ERQS	0.516	0.267	0.247	13.69	3	113	<0.001
	ERQR	0.410	0.168	0.146	7.619	3	113	<0.001
Full model	SWLS	0.739	0.546	0.521	22.03	6	110	<0.001

direct and total effects of karate training on satisfaction with life, controlled for gender and dichotomized age, with self-control, suppression, and reappraisal as mediating variables.

A similar value (R^2 = 0.506, $p < 0.001$) was obtained for the mediation analysis, which was calculated without controlling for gender and age effects; the difference in R^2 between the two analyses was found to be small but statistically significant ($\Delta R^2 = 0.040$, $p = 0.010$). Regression models for the mediating variables were also significant and achieved R-squared values ranging from 0.168 to 0.267 (see **Table 2** for details).

Table 3 shows the parameter estimates for the indirect, direct, and total effects of karate training on satisfaction with life, controlled for gender and dichotomized age, with self-control, suppression, and reappraisal as mediating variables. The direct effect of karate training on satisfaction with life did not differ significantly from zero. The karate training was indirectly associated with life satisfaction via the indirect paths that lead through self-control and reappraisal. Karate practitioners had higher self-control and reappraisal, which were associated with greater satisfaction with life. The scores on the Suppression scale of ERQ did not mediate the effect of karate training. Females scored significantly higher than males on BSCS, SWLS and the Reappraisal scale of ERQ; they scored significantly lower on the Suppression scale of ERQ. As compared to the younger group, respondents aged 25–45 years scored significantly higher on BSCS and on both scales of ERQ, but not on SWLS (see **Table 3** and **Figure 1** for details).

DISCUSSION

The current study is the first to explore the intermediate impact of self-control and emotion regulation on the relationship between karate training and satisfaction with life. In our research, we tested whether self-control and emotion regulation help to understand the relationship between sport training and satisfaction with life.

We found that karate training is indirectly related to satisfaction with life through the indirect pathways that lead through self-control and cognitive reappraisal. That is, karate

TABLE 3 | Indirect, direct, and total effects of karate training on satisfaction with life in regression-based mediation analysis with self-control, suppression, and reappraisal as mediating variables, and with gender and dichotomized age as covariates.

				95% confidence interval		
Effect type	**Effect**	**Estimate**	**SE**	**Lower**	**Upper**	**β**
Indirect	TRAINING ⇒ BSCS ⇒ SWLS	1.078	0.368	0.505	1.991	0.156
	TRAINING ⇒ ERQS ⇒ SWLS	−0.002	0.048	−0.127	0.081	0.000
	TRAINING ⇒ ERQR ⇒ SWLS	0.546	0.283	0.130	1.254	0.079
Component	TRAINING ⇒ BSCS	4.831	1.188	2.557	7.233	0.331
	BSCS ⇒ SWLS	0.223	0.053	0.118	0.327	0.471
	TRAINING ⇒ ERQS	−0.234	0.789	−1.772	1.289	−0.024
	ERQS ⇒ SWLS	0.008	0.058	−0.106	0.121	0.012
	TRAINING ⇒ ERQR	3.357	0.977	1.386	5.213	0.295
	ERQR ⇒ SWLS	0.163	0.06	0.048	0.286	0.268
Direct	TRAINING ⇒ SWLS	0.148	0.553	−0.980	1.185	0.023
Total	TRAINING ⇒ SWLS	1.770	0.579	0.634	2.905	0.245
Covariates	GENDER ⇒ BSCS	3.203	1.525	0.009	6.048	0.191
	GENDER ⇒ ERQS	−5.082	0.971	−6.974	−3.193	−0.450
	GENDER ⇒ ERQR	2.591	0.915	0.803	4.423	0.199
	GENDER ⇒ SWLS	1.717	0.592	0.598	2.936	0.217
	AGE_D ⇒ BSCS	5.249	1.281	2.761	7.816	0.358
	AGE_D ⇒ ERQS	1.904	0.832	0.256	3.541	0.192
	AGE_D ⇒ ERQR	2.925	1.004	0.957	4.887	0.256
	AGE_D ⇒ SWLS	0.893	0.541	−0.154	1.968	0.129

SE, standard error; β, standardized parameter estimate; BSCS, Brief Self-Control Scale; ERQS, Suppression scale in Emotion Regulation Questionnaire; ERQR, Reappraisal scale in Emotion Regulation Questionnaire; SWLS, Satisfaction with Life Scale. Coding for TRAINING: 0 | 1 (No | Yes). Coding for GENDER: 0 | 1 (Male | Female). AGE_D: Age in years dichotomized by a median split, coded 1 | 2 (18–24 years, n = 63 | 25–45 years, n = 54).

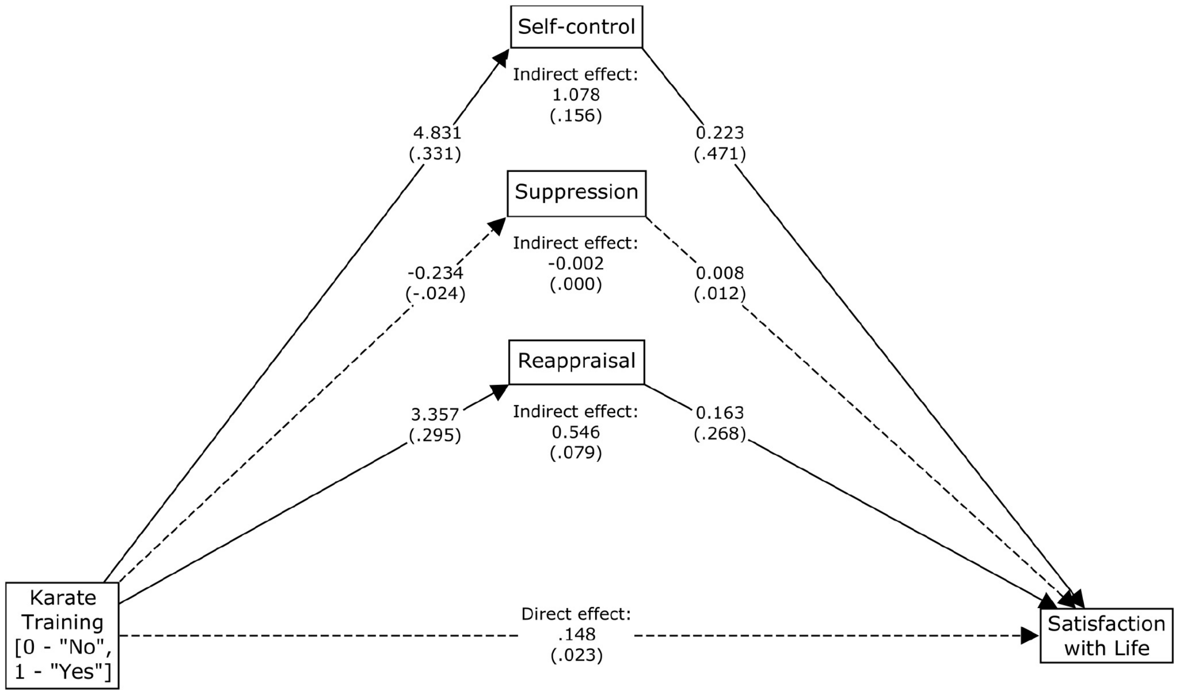

FIGURE 1 | Diagram presenting raw and standardized (in brackets) parameter estimates obtained in the linear regression-based mediation analysis of indirect, direct and total effects of karate training on satisfaction with life with self-control, suppression, and reappraisal as mediating variables, and with gender and dichotomized age as covariates. Solid lines–significant effect; dashed lines–insignificant effect. Parameter estimates were tested for significance using bias-corrected bootstrap confidence intervals. Effects of gender and dichotomized age were estimated in mediation analysis but are not shown.

training is associated with high self-control and high cognitive reappraisal, which consequently increase life satisfaction. Our results are consistent with those obtained in previous studies, which showed that karate training increases quality of life and psychological well-being (Marie-Ludivine et al., 2010; Jansen et al., 2017) and enhances self-control (Lakes and Hoyt, 2004; Vertonghen and Theeboom, 2010; Messaoud, 2015). Sport practitioners use a wide range of flexible and effective emotion regulation strategies in response to the changing contexts and demands of situations (Kucharski et al., 2018). Additionally, it has been suggested (Madden, 1995) that the psychological benefits of martial arts training are greater than the benefits of other forms of physical activity. Coupled with our results, the association between self-control and well-being (Hofmann et al., 2014) suggests that karate training substantially affects life satisfaction.

Our results show that cognitive reappraisal mediated the effect of karate training on satisfaction with life, as opposed to expressive suppression, which did not mediate this effect. Previous findings also showed that cognitive regulatory strategies, such as reappraisal, can improve mood and foster emotional well-being (Balzarotti et al., 2016). Studies by Gross and John (2003) indicated that people who prefer reappraisal can cope with negative emotions more effectively and maintain better quality of interpersonal relationships. In contrast, the use of expressive suppression is associated with reduced well-being (Haga et al., 2007). The assessment of only the positive dimension of psychological well-being could explain that expressive suppression does not mediate the relationship between karate training and satisfaction with life. Meanwhile, expressive suppression, which is a non-adaptive form of emotion regulation could mediate the relationship between karate training and the negative aspect of psychological well-being (i.e., reduced quality of life). However, this supposition also requires further research, using tools to assess the negative aspects of psychological well-being, e.g., depressive symptoms or distress, etc. Coupled with our results, this suggests that only a more adaptive form of emotion regulation provides an intermediate link between karate training and high life satisfaction.

Our results indicate that karate training can have a positive impact on satisfaction with life. It was also shown that eastern martial arts training helps to significantly improve participants' self-control and reduce levels of aggression and impulsivity (Zivin et al., 2001; Vertonghen and Theeboom, 2010). Furthermore, a study conducted by Kimberley D. Lakes and William T. Hoyt (Lakes and Hoyt, 2004) indicates that adolescents participating in a 3-month intervention using martial arts training (Tae Kwon Do) scored better in self-control than those participating in standard physical activity training. Martial arts training may have beneficial effects on participants' self-control in various contexts. Therefore, karate training should be more widely included in extracurricular activities for children and adolescents. Karate training is especially useful for people prone to aggressive and impulsive behavior.

Strengths, Limitations, and Further Research Directions

This study examined relationships that had not been previously analyzed together and found that self-control and reappraisal fully mediate the impact of karate training on satisfaction with life. More than half of the variance in the dependent variable was accounted for by our mediation model, thus indicating that self-control and reappraisal explain substantially higher levels of trainees' satisfaction with life. We showed that the association between karate training and subjective well-being and life satisfaction can be explained by self-control and cognitive reappraisal.

Our study had also some limitations. First, since our study was preliminary and exploratory, it was conducted on a small sample which was taken from a small geographic area. A gender disparity in our sample was also observed. However, the gender proportions in our sample are consistent with the number of women in the Polish population of karate practitioners. A report by the Polish Central Statistical Office (Malinowska, 2019) shows that women make up approximately 30% of total karate trainees in Poland. In further studies, the sample size should be larger, and more women should be surveyed to examine whether gender moderates the relationships between karate training and satisfaction with life that are mediated by self-control and emotional regulation. Secondly, only a small range of controlled sociodemographic variables was included in our study; therefore, variables such as education, household situation, and material and professional status should also be included in future research. Moreover, comparing martial arts practitioners to other athletes should also be considered in future studies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

WP, LK, and RH-K developed the study concept and drafted the first manuscript. WP organized and conducted the survey. RH-K supervised the research. LK performed the statistical analysis, prepared the figure, and obtained the funding for publication costs. All authors contributed equally to the revision of the manuscript and approved the submitted version.

FUNDING

Funds for publication costs were granted to the authors on the basis of application number BN.302.147.2021.RN from a research subsidy for the maintenance and development of research potential that was awarded to the Pedagogical University in Krakow by the Polish Ministry of Education and Science.

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frontiers in Behavioral Neuroscience

BRIEF RESEARCH REPORT
published: 28 January 2022
doi: 10.3389/fnbeh.2021.834097

The Effect of Brief Stair-Climbing on Divergent and Convergent Thinking

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Recent studies show that even a brief bout of aerobic exercise may enhance creative thinking. However, few studies have investigated the effect of exercise conducted in natural settings. Here, in a crossover randomized controlled trial, we investigated the effect of a common daily activity, stair-climbing, on creative thinking. As experimental intervention, subjects were asked to walk downstairs from the fourth to the first floor and back at their usual pace. As control intervention, they walked the same path but using the elevator instead. Compared to using the elevator, stair-climbing enhanced subsequent divergent but not convergent thinking in that it increased originality on the Alternate Use Test (d = 0.486). Subjects on average generated 61% more original uses after stair-climbing. This is the first study to investigate the effect of stair-climbing on creative thinking. Our findings suggest that stair-climbing may be a useful strategy for enhancing divergent thinking in everyday life.

Keywords: acute aerobic exercise, stair-climbing, creativity, divergent thinking, alternate use test, insight problem-solving

OPEN ACCESS

Edited by:
Etsuro Ito,
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Specialty section:
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

Received: *13 December 2021*
Accepted: *27 December 2021*
Published: *28 January 2022*

Citation:
Matsumoto K, Chen C, Hagiwara K, Shimizu N, Hirotsu M, Oda Y, Lei H, Takao A, Fujii Y, Higuchi F and Nakagawa S (2022) The Effect of Brief Stair-Climbing on Divergent and Convergent Thinking. Front. Behav. Neurosci. 15:834097. doi: 10.3389/fnbeh.2021.834097

INTRODUCTION

Creativity or creative thinking, a high-level cognitive function, is the key to invention and innovation in many fields of human society, including but not limited to science, technology, industry, business, education, and art (Hennessey and Amabile, 2010; Sternberg and Kaufman, 2018). The development of effective tools to evaluate and strategies to enhance creative thinking, therefore, has attracted much attention in the past decades (Guilford, 1967b; Hennessey and Amabile, 2010; Sternberg and Kaufman, 2018). Creative thinking comprises two fundamental processes: divergent and convergent thinking. Whereas the former involves stretching beyond existing solutions to generate multiple, novel ones, the latter involves approaching a single correct, objective-appropriate solution (Guilford, 1967a). It has been shown that performance on tests of divergent and convergent thinking predicts creative potential and achievement in real-life as well as creativity evaluated by others (Cropley, 2000; Kim, 2008; Runco et al., 2010; Gralewski and Karwowski, 2019).

A recent, timely systematic review concluded that a single bout of aerobic exercise may enhance creative thinking (in particular divergent thinking, Aga et al., 2021). In the reviewed studies, divergent thinking was typically evaluated with the original or adapted versions of the Alternate Uses Test (AUT, Guilford, 1960; Torrance, 1966). In this test, subjects have to write down as many as possible unusual uses of common objects, such as "bricks." The number of generated uses (known as fluency), the number of conceptual categories the generated uses are from (flexibility), and the rareness of the uses (originality) are commonly employed as indicators of divergent thinking (Runco and Acar, 2012; Reiter-Palmon et al., 2019). Studies conducted in the laboratory have reported that aerobic workout or dance for approximately 20 min (Steinberg et al., 1997), walking on a treadmill for 4 min at a self-selected pace (Oppezzo and Schwartz, 2014) or 44 min at vigorous-intensity (Netz et al., 2007), or cycling on an ergometer for 15 min at roughly light to moderate intensity (Aga et al., 2021) enhanced one or multiple indicators of divergent thinking. Convergent thinking, in contrast, was unaffected or uninvestigated in these studies.

Despite these encouraging findings, whether aerobic exercise commonly conducted in everyday life enhances creative thinking remains unclear. To our knowledge, only two studies have investigated the effect of acute aerobic exercise conducted in natural, real-life settings. One study investigated the effect of walking through a university campus (Oppezzo and Schwartz, 2014), and the other the effect of a 45-min physical education class featuring aerobic games (Román et al., 2018), both of which reported enhanced divergent thinking after the intervention. Neither studies, however, evaluated convergent thinking.

In the present study, therefore, we aimed to advance our understanding of the impact of aerobic exercise conducted in everyday life on both divergent and convergent thinking, by focusing on a common physical activity, stair-climbing. Climbing stairs at comfortable or fast paces and with or without carrying groceries or other loads, has been a recommended physical activity in many governmental guidelines, such as those of the United States (US Department of Health and Human Services, 2018) and Japan (Japanese Ministry of Health Labour and Welfare [JMHLW], 2013). Based on previous reports that stepping over obstacles and precision stepping activate the prefrontal cortex (PFC), a primary neural substrate of divergent thinking, cognitive flexibility, and executive functions in general (Yuan and Raz, 2014; Dajani and Uddin, 2015; Wu et al., 2015), we hypothesized that a brief stair-climbing intervention enhances divergent and convergent thinking.

MATERIALS AND METHODS

Participants

The study was approved by the authors' Institutional Review Board and carried out in accordance with the Declaration of Helsinki. All subjects provided written informed consent. The study was also preregistered on the University hospital Medical Information Network Clinical Trial Registry (UMIN-CTR). Using data from Oppezzo and Schwartz (Oppezzo and Schwartz, 2014) that reported an effect size of d = 0.70 (Experiment 1, Walking versus Siting within-subjects), we estimated that to detect such an effect size with power = 0.8, alpha = 0.05, two-sided, 19 subjects were necessary. Considering dropout cases, we recruited 22 subjects (12 males, 10 females, including 19 medical undergraduates and three graduate students; age: 21.36 ± 1.33 years). The inclusion criterion was being in their twenties. The exclusion criteria were reporting any current psychiatric disorders (or currently psychiatric examinations) and having participated our previous studies of creative thinking.

Design and Procedure

Before the laboratory visit, subjects received instructions to get enough sleep and refrain from doing intense physical activities and from smoking and consuming drinks with caffeine for at least 2 h before coming to the laboratory. They were also asked to change the experimental schedule if they were sick.

Upon arriving, subjects first provided written informed consent after receiving a detailed description of the study. They then filled out questionnaires and answered their demographic information together with a few questions to check if they have followed the above instructions. Subjects also indicated their baseline mood using the Positive and Negative Affect Schedule [PANAS, Watson et al., 1988].

The study was a crossover randomized controlled trial with a posttest comparison design (**Figure 1**). Subjects were assigned to receive a brief stair-climbing and control intervention in a counter balanced order and immediately after each intervention they conducted tests of creative thinking. The trial was repeated on two separate days to investigate the effect on divergent and convergent thinking, respectively. The order of the divergent and convergent thinking tests was also randomized. Statistical comparisons showed that subjects reported similar baseline positive affect (paired t-test, t = −0.697, p = 0.493) and negative

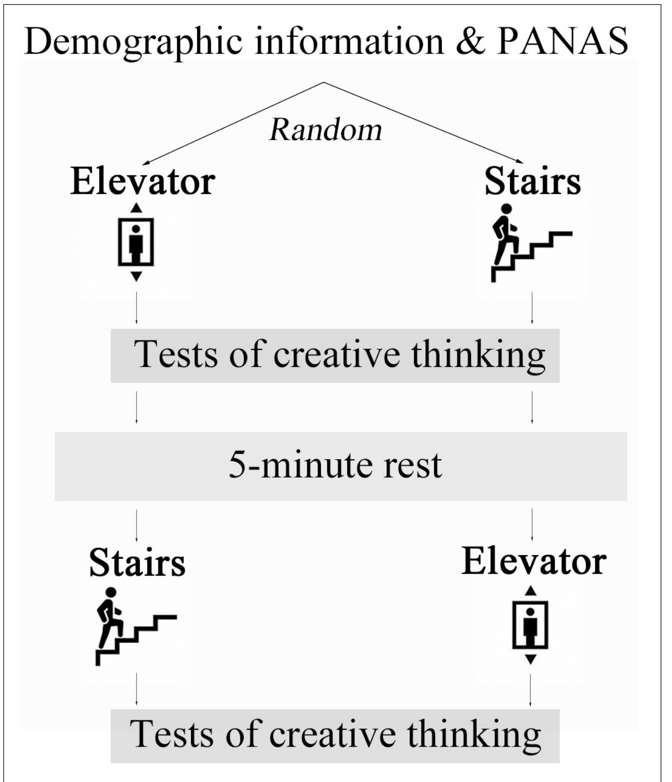

FIGURE 1 | Schematic illustration of the procedure.

affect (Wilcoxon signed-rank test, $Z = -1.267$, $p = 0.205$) on the two test days, suggesting that the randomization was appropriate.

During both interventions, subjects wore an Apple Watch (Series 4, Apple Inc.) to measure their heart rate and time taken to finish the intervention. The accuracy of Apple Watch for the measurement of heart rate has been established (Wang et al., 2017). Immediately after each intervention, subjects also indicated their current mood on a visual analog scale in terms of pleasure, relaxation, and vigor (Aga et al., 2021). As a washout period, after the first phase of intervention and creative thinking test, subjects rested for 5 min. After finishing the last creative test on the second test day (i.e., at the end of the experiment), subjects also filled out the International Physical Activity Questionnaire (IPAQ) to report their levels of vigorous physical activity, moderate physical activity, and walking in the past 7 days.

Intervention

For the stair-climbing intervention, starting from the laboratory room on the fourth floor, subjects were asked to walk downstairs to the first floor and back after approaching but without stepping out of the entrance of the building. A schematic illustration of this round-trip path and the layout of the first and fourth floors is shown in **Supplementary Figure 1**. One flight had 21 stairs in between. For the control intervention, they were asked to walk the same path but using the elevator instead. Subjects were asked to walk at their usual pace for both interventions. They were also asked to remain quiet and not to speak with anyone they might encounter throughout the interventions.

The rationale of selecting this intensity of exercise intervention (i.e., walking downstairs of three flights and then back) was three-fold. Firstly, this intensity (in Metabolic equivalents) was roughly equal to that of treadmill walking for 4 min as used in Oppezzo and Schwartz (Oppezzo and Schwartz, 2014), as estimated based on our pilot testing. Secondly, we could also have set the walking distance to five flights since we also had laboratory rooms on the sixth floor; however, in our pilot testing, subjects felt somewhat tired and short of breath, which did not allow us to start the creative thinking tests immediately after the intervention. Thirdly, based on our pilot survey with staffs and students in our department, most people tended to use stairs for two or three flights.

The building in which we conducted the experiment was a research building with six floors and nine clinical departments. The elevator was most crowded before 9:00 in the morning and after 17:00 in the afternoon because of the commuting traffic, and was moderately crowded between 12:00 and 14:00 because of the lunch break. The experiment was conducted between 9:00–12:00 am and 14:00–17:00 pm, during which time the traffic was generally considered mild.

Divergent Thinking

The commonly employed AUT was used to evaluate divergent thinking. In this test, given 4 min, subjects had to think of original and unusual uses of three common objects (e.g., “brick”) and write their answers on a blank paper sheet of A4-size. Different objects were used for each phase of intervention, the order of which was also randomized for each subject.

Following previous studies, fluency, flexibility, and originality were employed as indicators of divergent thinking (Runco and Acar, 2012; Reiter-Palmon et al., 2019). Fluency was defined as the total number of unusual uses (excluding the common use of each object). Flexibility was defined as the total number of conceptual categories the uses are from (e.g., “dumbbell” and “objects for muscle training” belong to the same conceptual category). Originality was the rareness of the uses and here defined according to the conceptual category of the uses. That is, only if a single participant generated use(s) from a specific conceptual category, that category was considered original; if two participants generated use(s) from the same conceptual category, the category was considered original for neither of them.

Before scoring all responses, the primary coder (i.e., the first author) first received extensive training with the scoring method. Using data from our previous study, the primary coder reached almost perfect agreement (Cohen, 1960) with our previous coder, as indicated by Cohen’s $\kappa = 0.970$ and 0.812 for flexibility and originality, respectively. After training, the primary coder scored all participants while staying blinded to the intervention order. To further ensure reliability, we also asked a secondary coder to score responses for a randomly selected object. The two coders reached an agreement of $\kappa = 1.000$ and 0.789 for flexibility and originality, respectively.

Convergent Thinking

The matchstick arithmetic problems created by Knoblich et al. (1999) were used to measure convergent thinking. Each problem was shown as an incorrect equation written with Roman numerals made by matchsticks and subjects had to move one stick to make the equation correct. For instance, for the problem of IV = III + III, the correct answer was to move one stick from the left side of “IV” to its right side to form “VI.” Three different types of problems depending on the way of moving the matchstick were selected for each set of divergent thinking test (administered after each phase of intervention). Based on our pilot testing, the time limit was set to 4 min. The number of correctly solved problems was used as the indicator of convergent thinking.

At the beginning of the experiment on the test day of convergent thinking, all subjects were first trained to be able to recognize the Roman numerals. After they finished the second phase of convergent thinking test, subjects were also asked if they had ever seen any of the matchstick problems tested. No subjects had seen exactly the same problems before the study.

Statistical Analysis

The statistical analysis was conducted with IBM SPSS Statistics 26.0. Due to non-normal distribution based on the Shapiro–Wilk test, Wilcoxon signed-rank tests were used to compare divergent and convergent thinking indicators after the stair-climbing versus control intervention. Two-way repeated measures ANOVAs were used investigate the effect of the test day (divergent versus convergent thinking) and the intervention (stair-climbing versus control) on heart rate, time taken to return to the laboratory room, and post-intervention mood. G*Power Version 3.1.9.7

(Faul et al., 2007) was used for calculating effect sizes. $P < 0.05$ was considered significant.

RESULTS

Heart Rate, Time Taken, and Mood Measures

As reported in **Table 1**, two-way repeated measures ANOVAs indicated a significant effect of intervention on heart rate ($p < 0.001$) and time taken to return to the laboratory room ($p < 0.001$), while the effect of test day and the intervention and test day interaction remained insignificant. The data on different test days were therefore combined together and plotted in **Figure 2A**. As can be seen, compared to using the elevator, stair-climbing increased heart rate (109.66 ± 11.198 versus 91.89 ± 11.418 bpm, $d = 3.547$) and cost less time (173.82 ± 23.890 versus 228.98 ± 57.760 s, $d = 0.937$). There were no significant effect of the intervention, test day, or their interaction on the post-intervention mood measures (**Figure 2B** and **Table 1**).

Divergent and Convergent Thinking

Scatterplots of the data of divergent and convergent thinking are shown in **Figure 3**. Wilcoxon signed-rank tests indicated that compared to using the elevator, stair-climbing significantly increased originality ($Z = 1.977$, $p = 0.048$, $d = 0.486$) but not fluency ($Z = 0.164$, $p = 0.870$, $d = 0.056$) or flexibility ($Z = 0.196$, $p = 0.845$, $d = 0.076$) on the AUT. Thus, stair-climbing increased divergent thinking not because subjects thought of more uses (as there was no significant difference in fluency) but because they thought of more original uses. To further verify this conclusion, we divided the number of original uses by the number of total uses generated for each subject. After using the elevator, subjects produced 2.3 ± 1.461 original uses for every 10 generated uses. In contrast, after stair-climbing, they produced 3.7 ± 2.246 original uses for every 10 generated uses. This difference was significant as indicated by a Wilcoxon signed-rank test ($Z = 2.207$, $p = 0.027$, $d = 0.532$). In other words, compared to using the elevator, subjects on average generated 61% more original uses after stair-climbing. With regards to convergent thinking, subjects' performance on the matchstick test did not differ after using the elevator versus after stair-climbing ($Z = 0.428$, $p = 0.669$, $d = 0.085$). Lastly, we also investigated if the effect of stair-climbing on originality was associated with subjects' regular physical activity level. The results, however, indicated no significant correlations between the change of originality and total physical activity, vigorous physical activity, moderate physical activity, or walking (all $p > 0.503$).

DISCUSSION

To our knowledge, this is the first study to investigate the effect of stair-climbing on creative thinking. We found that compared to using the elevator, stair-climbing enhanced subjects' originality on the AUT, indicating improved divergent thinking. Subjects on average generated 61% more original uses after stair-climbing than after using the elevator. In contrast, stair-climbing did not affect convergent thinking as evaluated by the matchstick arithmetic problems. As a daily physical activity, stair-climbing increased subjects' heart rate more than using the elevator ($d = 3.547$). Using the commonly employed formula (220-age) as an estimation of maximum heart rate and considering the average age of all subject was 21.36 years, the intensity of the stair-climbing here (with a mean heart rate of 109.66 bpm) was equal to 55% maximum heart rate, or very light (American College of Sports Medicine [ACSM], 2013). Our results suggest that stair-climbing in very light intensity in a natural, real-life setting may enhance divergent thinking. Furthermore, in our experiment, because of the waiting time to use the elevator, stair-climbing also cost less time ($d = 0.937$). Thus, compared to using the elevator, at least for people at the fourth floor, stair-climbing may be a preferred moving method because of its higher efficiency and divergent thinking-enhancing effect.

Among the three measures of divergent thinking, stair-climbing enhanced originality but not fluency or flexibility. Whereas the explanation of such result is unclear, one possibility is that stair-climbing did not change vigor or arousal level in the present study and the latter, however, is required for the enhancing of fluency and flexibility (Aga et al., 2021). Nevertheless, compared to fluency and flexibility, originality is generally considered more important and the key component of divergent thinking (Runco and Acar, 2012; Oppezzo and Schwartz, 2014).

Based on previous reports that stepping over obstacles and precision stepping activate the prefrontal cortex (PFC), a primary neural substrate of divergent thinking, cognitive flexibility, and executive functions in general (Yuan and Raz, 2014; Dajani and Uddin, 2015; Wu et al., 2015), we hypothesized that stair-climbing enhances divergent and convergent thinking. Our hypothesis, however, was only partially supported. Our results are consistent with Oppezzo and Schwartz

TABLE 1 | The results of two-way repeated measures ANOVAs of heart rate, time taken to return to the laboratory room, and post-intervention mood measures.

	Heart rate	Time taken	Pleasure	Relaxation	Vigor
Intervention	**F = 366.328, p = 0.000*** **	**F = 44.112, p = 0.000*** **	F = 0.516, p = 0.481	F = 2.008, p = 0.171	F = 2.171, p = 0.155
Test day	F = 0.558, p = 0.463	F = 0.824, p = 0.374	F = 0.366, p = 0.551	F = 0.485, p = 0.494	F = 0.002, p = 0.966
Interaction	F = 0.246, p = 0.625	F = 0.883, p = 0.358	F = 3.008, p = 0.098	F = 0.520, p = 0.479	F = 0.145, p = 0.707

****p < 0.001. Statistically significant results are shown in bold.*

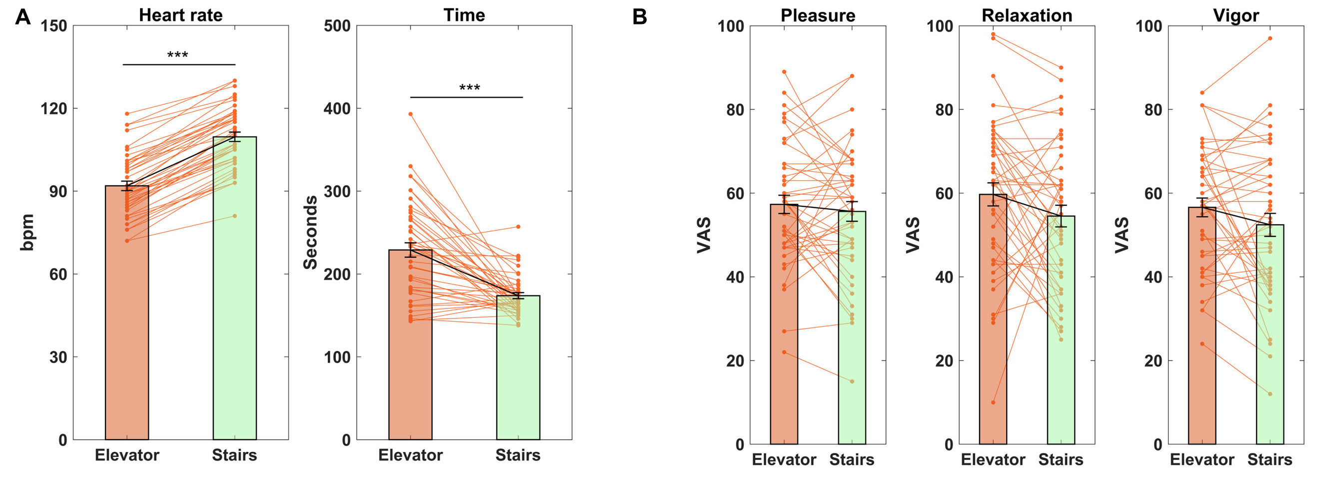

FIGURE 2 | Intervention effect on heart rate, time taken to return to the laboratory room, and mood. **(A)** Heart rate and time taken; **(B)**, mood. The data on different test days are combined and plotted together. ***$p < 0.001$ bpm, beat per minutes. VAS, visual analog scale. Data shown as mean ± SE.

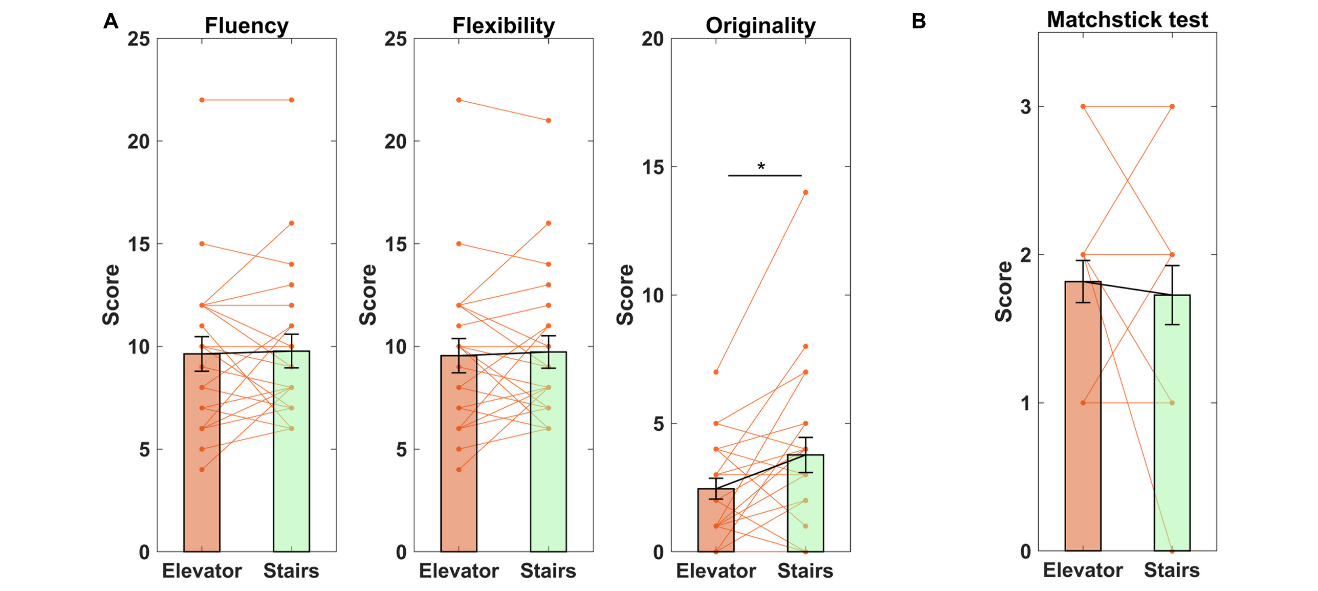

FIGURE 3 | Intervention effect on divergent and convergent thinking. **(A)** Alternate Uses Test; **(B)**, Matchstick test. *$p < 0.05$. Data shown as mean ± SE.

(Oppezzo and Schwartz, 2014), who reported that walking on a treadmill for 4 min at a self-selected pace improved divergent (evaluated by the AUT) but not convergent thinking (evaluated by the compound remote-association test). It is unclear why walking affects divergent but not convergent thinking despite the observation that both divergent and convergent thinking are related to the functioning of the PFC (Kleibeuker et al., 2013; Yuan and Raz, 2014; Dajani and Uddin, 2015; Wu et al., 2015; Peña et al., 2019). One possibility might be that the impact of aerobic exercise on convergent thinking depends on post-exercise mood (Aga et al., 2021), which, however, is not affected by walking or stair-climbing at very light intensity. This possibility remains to be tested by future well-designed studies. Regarding the neurobiological basis of the divergent thinking-enhancing effect of walking and stair-climbing, another potential mechanism in addition to the PFC may be the release of dopamine in response to physical activity (Chen et al., 2016, 2017). This proposal is based on the finding that dopamine is relevant to cognitive flexibility (Klanker et al., 2013) and associative or reinforcement learning (Chen, 2015; Chen et al., 2015), two cognitive processes underlying divergent thinking (Benedek et al., 2012).

As an everyday life physical activity, climbing stairs at comfortable or fast paces and with or without carrying groceries or other loads, has been a recommended physical activity in many governmental guidelines (Japanese Ministry of Health Labour and Welfare [JMHLW], 2013; US Department of Health and Human Services, 2018). Few studies, however, have investigated s the specific physical and mental health benefits of stair-climbing. Allison et al. (2017) reported that brief intense stair-climbing involving 3 × 20 s "all-out" efforts produced robust physiological changes, including increased heart rate and blood lactate. Stenling et al. (2019) reported that compared to after no exercise, subjects had increased heart rate and felt more energetic, less tense, and less tired after three 1-min stair-climbing sessions (with 1-min recovery in between). In this study, males but not females showed better switching performance and neither showed improved inhibitory control ability (Stenling et al., 2019). These results, however, need to be replicated because their sample size was small (n = 11 for males). Our current study adds novel evidence to the literature of stair-climbing that a brief very light intensity stair-climbing enhances divergent thinking. As it has been reported that regular walking is associated with improved divergent but not convergent thinking (Nakagawa et al., 2020; Chen et al., 2021), future research may further investigate if regular stair-climbing has similar cognitive benefits.

Our study also had several limitations. Firstly, we used stair-climbing in a natural, real-life setting as our intervention, the intensity of which therefore was heterogeneous for each subject. This is different from heart rate reserve or aerobic capacity reserve-based exercise prescriptions (American College of Sports Medicine [ACSM], 2013). It is possible that people with higher aerobic capacity tend to use stairs more often and for more flights, although they may be unable to choose which floor to use for work or living. Secondly, we only tested stair-climbing as a round-trip between the fourth and the first floors. The intervention was considered very light in intensity and it is possible that stair-climbing at this very light intensity was unable to effectively enhance divergent thinking in some subjects. Future research is thus required to test stair-climbing at higher intensities to see if it boosts divergent thinking in all subjects. Thirdly, we used but one common test for the evaluation of divergent and convergent thinking, respectively. To validate our results, future studies should also test the effect of stair-climbing on other popular tests of divergent and convergent thinking. Fourthly, we limited our subjects to those in their twenties in order to exclude the confounding effect of age and improve statistical power. This, however, also limits the generalization of our findings to other populations. Future studies with more diverse subjects are needed to test whether our findings generalize to other populations.

CONCLUSION

In a randomized controlled trial with a within-subjects crossover posttest comparison design, we found that compared to using the elevator, a brief stair-climbing intervention involving a round-trip walking for three flights enhanced divergent thinking in a sample of healthy young adults. Subjects on average generated 61% more original uses after stair-climbing than after using the elevator. Furthermore, stair-climbing cost less time compared to using the elevator. Our findings suggest that stair-climbing may be an efficient and useful strategy for enhancing divergent thinking in everyday life.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Yamaguchi University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CC and SN: conceptualization. KM, CC, KH, NS, YO, HL, and AT: methodology. KM and CC: formal analysis and writing—original draft preparation. KM, CC, NS, and MH: investigation. YF and FH: resources. All authors contributed to writing—review and editing and have read and agreed to the published version of the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnbeh.2021.834097/full#supplementary-material

Supplementary Figure 1 | Schematic illustration of the round-trip path and the layout of the first and fourth floors used for the interventions.

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frontiers in Behavioral Neuroscience

BRIEF RESEARCH REPORT
published: 15 March 2022
doi: 10.3389/fnbeh.2022.853150

Cognitive Improvement After Aerobic and Resistance Exercise Is Not Associated With Peripheral Biomarkers

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OPEN ACCESS

Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

Received: 12 January 2022
Accepted: 21 February 2022
Published: 15 March 2022

Citation:
Ando S, Komiyama T, Tanoue Y, Sudo M, Costello JT, Uehara Y and Higaki Y (2022) Cognitive Improvement After Aerobic and Resistance Exercise Is Not Associated With Peripheral Biomarkers. Front. Behav. Neurosci. 16:853150. doi: 10.3389/fnbeh.2022.853150

The role of peripheral biomarkers following acute physical exercise on cognitive improvement has not been systematically evaluated. This study aimed to explore the role of peripheral circulating biomarkers in executive performance following acute aerobic and resistance exercise. Nineteen healthy males completed a central executive (Go/No-Go) task before and after 30-min of perceived intensity matched aerobic and resistance exercise. In the aerobic condition, the participants cycled an ergometer at 40% peak oxygen uptake. In the resistance condition, they performed resistance exercise using elastic bands. Before and after an acute bout of physical exercise, venous samples were collected for the assessment of following biomarkers: adrenaline, noradrenaline, glucose, lactate, cortisol, insulin-like growth hormone factor 1, and brain-derived neurotrophic factor. Reaction time decreased following both aerobic exercise and resistance exercise ($p = 0.04$). Repeated measures correlation analysis indicated that changes in reaction time were not associated with the peripheral biomarkers (all $p > 0.05$). Accuracy tended to decrease in the resistance exercise condition ($p = 0.054$). Accuracy was associated with changes in adrenaline [$r_{rm}(18) = -0.51$, $p = 0.023$], noradrenaline [$r_{rm}(18) = -0.66$, $p = 0.002$], lactate [$r_{rm}(18) = -0.47$, $p = 0.035$], and brain-derived neurotrophic factor [$r_{rm}(17) = -0.47$, $p = 0.044$] in the resistance condition. These findings suggest that these peripheral biomarkers do not directly contribute to reduction in reaction time following aerobic or resistance exercise. However, greater sympathoexcitation, reflected by greater increase in noradrenaline, may be associated with a tendency for a reduction in accuracy after acute resistance exercise.

Keywords: cognition, brain, reaction time, executive function, catecholamines

INTRODUCTION

Acute aerobic exercise at light/moderate intensity improves cognitive performance (Chang et al., 2012; McMorris, 2021). The effects of acute resistance exercise on cognitive performance have received increasing attention, and recent reviews have suggested that resistance exercise also has the potential to improve cognitive performance (Soga et al., 2018; Wilke et al., 2019). It is widely speculated that an increase in arousal is responsible for these improvements in cognitive performance (Chang et al., 2012; Ando et al., 2020; McMorris, 2021). However, the mechanism(s) responsible for cognitive improvement following acute aerobic and resistance exercise remain unclear. Specifically, the role of peripheral biomarkers following acute physical exercise on cognitive improvement has not been systematically evaluated.

Adrenaline and noradrenaline are important for the adaptive response to physiological stressors through the activation of the sympathoadrenomedullary system (Danese et al., 2018). In this context, there is some evidence in the literature that acute physical exercise increases circulating catecholamine concentrations (Pontifex et al., 2019; McMorris, 2021). Although peripheral adrenaline and noradrenaline do not easily traverse the blood-brain barrier (Cornford et al., 1982), increased circulating adrenaline and noradrenaline activate β-adrenoceptors on the afferent vagus nerve, which terminates in the nucleus tractus solitarii (NTS) within the blood-brain barrier (McGaugh et al., 1996). Noradrenergic cells in the NTS also project to the locus coeruleus and stimulate noradrenaline synthesis and release to other regions of the brain (McMorris, 2016). Thus, increased circulating adrenaline and noradrenaline may, at least in part, lead to an improvement in executive performance.

Blood glucose is the primary source of energy for the brain (Gold, 1995) and recent studies indicate that increased blood lactate after high-intensity interval exercise is associated with attentional or executive performance (Tsukamoto et al., 2016; Hashimoto et al., 2018; Herold et al., 2022). These findings suggest that enhanced lactate metabolism may contribute to executive improvements. However, the role of blood lactate following acute light intensity aerobic and resistance exercise is relatively unknown. Similarly, in response to acute stress, cortisol is released by the adrenal cortex and is regulated by the hypothalamic–pituitary–adrenal (HPA) (Costello et al., 2018). Tsai and colleagues reported that alterations in cortisol level after resistance exercise are associated with electrophysiological activity (i.e., P3 amplitude) (Tsai et al., 2014). These findings suggest that alterations in circulating cortisol level could be linked to executive performance following acute physical exercise.

Acute resistance exercise increases peripheral insulin-like growth hormone factor 1 (IGF-1) (Rubin et al., 2005; Rojas Vega et al., 2010; Tsai et al., 2014, 2018). Acute aerobic (Huang et al., 2014; Tsai et al., 2018), and resistance (Marston et al., 2017) exercise increases peripheral brain-derived neurotrophic factor (BDNF). Rodent studies suggest that increases in IGF-1 are related to improvements in learning and spatial memory after a period of training (Ding et al., 2006; Cassilhas et al., 2012). In contrast to adrenaline and noradrenaline, BDNF crosses the blood–brain barrier in both directions (Pan et al., 1998) and it has also been speculated that elevated BDNF might contribute to improvements in executive performance/memory after acute physical exercise (Ferris et al., 2007; Griffin et al., 2011; Piepmeier and Etnier, 2015; Borror, 2017). Indeed, improvement in executive performance was associated with exercise-related changes in BDNF (Hwang et al., 2016). However, IGF-1 and BDNF appears to play a crucial role in angiogenesis, synaptogenesis, and neurogenesis following long-term exercise (Cotman and Berchtold, 2002; Voss et al., 2011; Nieto-Estevez et al., 2016) and further studies are necessary to understand whether transient increases in IGF-1 and BDNF contribute to an improvement in executive performance following acute physical exercise.

Acute light aerobic exercise has been suggested to improve executive performance (Chang et al., 2012), and peripheral adrenaline and noradrenaline concentrations increase after acute light aerobic exercise (i.e., 40% maximal oxygen uptake) (McMurray et al., 1987). If changes in peripheral biomarkers, such as adrenaline and noradrenaline, are associated with alterations of the performance of executive functioning, it seems reasonable to hypothesize that an association between peripheral biomarkers and executive functioning can be observed even after light-intensity physical exercise. Lactate production in response to acute exercise depends on type of exercise (i.e., aerobic or resistance) (Hashimoto et al., 2021). Acute light aerobic exercise does not increase blood lactate concentration (Ivy et al., 1980). Conversely, resistance exercise at low intensity using elastic bands appear to increase blood lactate (Yasuda et al., 2014). Furthermore, an acute bout of resistance exercise, but not aerobic exercise, is a physiological stimulus for acute increases in IGF-1 (Gregory et al., 2013). These suggest that changes in some peripheral biomarkers (e.g., lactate and IGF-1) may be greater after resistance exercise relative to aerobic exercise. Hence, comparing the effects of aerobic and resistance exercise on executive performance and peripheral biomarkers can help to elucidate the common or divergent molecular mechanisms driving changes in cognitive performance after different types of acute physical exercises (i.e., aerobic vs. resistance exercises).

Accordingly, this study sought to investigate the relationship between peripheral circulating biomarkers and executive performance following acute, intensity matched, aerobic and resistance training exercise. We tested the hypothesis that: (i) acute aerobic and resistance exercise would improve executive performance, (ii) peripheral biomarkers would be associated with this performance, and (iii) the differential effects of aerobic and resistance exercise on peripheral biomarkers would delineate the specific contribution of these biomarkers to improvement in executive performance.

MATERIALS AND METHODS

Participants

Nineteen healthy males volunteered to participate in this study [age: 22.5 ± 2.3 year; body weight: 1.71 ± 0.06 m; body mass: 66.2 ± 7.6 kg; peak oxygen uptake ($\dot{V}O_{2peak}$): 48.2 ± 7.1 ml kg min^{-1}]. All participants were physically active and met the following criteria: (i) right handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971); (ii) low-risk status for physical exercise-related adverse events assessed by Physical Activity Readiness Questionnaire (Warburton et al., 2011); and (iii) no history of cardiovascular, cerebrovascular, or respiratory disease (self-report). All participants gave their written informed consent prior to participation. Sample size was calculated using G-power (version 3.1) (Faul et al., 2009) based on our pilot data which suggested that a reduction in reaction time (RT) after aerobic exercise at 40% $\dot{V}O_{2peak}$ was ∼28 ms (Cohen's day effect size of 0.4). Accordingly, a minimum of 15 participants were required to achieve a power of 80% with an alpha of 0.05. The participants were instructed to abstain from any strenuous exercise for 24 h and food, caffeine and alcohol for 12 h prior to the laboratory visit. All experimental procedures adhered to the standards set by the latest revision of the declaration of Helsinki, except for registration in a database, and were approved by the ethics committee of Fukuoka University (2015-09-01).

Cognitive Task

Central executive function was assessed using a Go/No-Go task. The task was completed on a laptop computer (Let's note CF-R4, Panasonic, Osaka, Japan) placed 80 cm from the participants. The participants performed the cognitive task sitting on a chair. The details of the cognitive task are described in detail elsewhere (Ando et al., 2013). Briefly, the participants were required to either respond (Go trial) or not (No-Go trial) according to the stimulus. A shift-key on the keyboard was used to perform the cognitive task. The participants pressed the key using the right index finger. A total of 30 trials were completed. Both RT and accuracy of the task were used to assess executive performance. Omitting a response in a Go trial or performing an incorrect response in a No-Go trial was regarded as an error trial. Accuracy of the task was calculated as number of correct response/total number of trials.

Experimental Procedure

This study employed a within-participants pre-test post-test crossover comparison in line with the taxonomy provided by Pontifex et al. (2019). The experiment was performed over three non-consecutive days with intervals of at least 3 days between experimental sessions. Throughout the experiment, the ambient temperature was maintained at 22°C and the relative humidity was controlled approximately at 50%. On the first day, the participants practiced the cognitive task until they were familiar with the task to minimize the impact of a learning effect. Thereafter, the participants performed a maximal exercise test to exhaustion on a cycle ergometer (75XLII, COMBI Wellness, Tokyo, Japan). After a warm-up period at 10 W for 1 min, the test was initiated with 20 W increments every minute in a ramp manner. Participants were instructed to maintain a cadence of 60 revolutions per min (rpm), and the test was terminated when they were unable to maintain a cadence of >40 rpm. Minute ventilation, oxygen uptake, fraction of end-tidal CO_2, and O_2 were recorded using a gas analysis system (ARCO-2000, ARCO System, Chiba, Japan), and $\dot{V}O_{2peak}$ was determined as the highest value attained over the course of 1 min. Exercise intensity at 40% $\dot{V}O_{2peak}$ (90 ± 13 watts) was subsequently calculated for aerobic exercise.

On the second and third days of the experiment, the experiments were performed on the same time to minimize circadian effects. At the beginning of the experiment, venous blood sample was collected from the antecubital vein for the analyses of adrenaline, noradrenaline, cortisol, IGF-1, and BDNF analysis. The left earlobe was pricked with a safety lancet and 2 μL capillary blood was collected for glucose and lactate analysis. Systolic blood pressure and diastolic blood pressure were measured from the right arm in a sitting position (HEM-705IT, Omron Healthcare, Kyoto, Japan). Mean arterial pressure (MAP) was subsequently calculated. Then, the participants performed the first cognitive task. After the cognitive task, the participants performed either aerobic or resistance exercise for 30 min. The order of exercise type was randomly counterbalanced. Immediately after the exercise, venous and capillary blood samples were collected, and blood pressure was measured. Then, the participants performed the second cognitive task.

Several studies have compared the effects of aerobic and resistance exercise on cognitive performance using a randomized crossover design (Pontifex et al., 2009; Alves et al., 2012; Harveson et al., 2016; Dunsky et al., 2017). However, exercise intensity is one of the key factors that determine the exercise-cognition interaction (Chang et al., 2012) and these previous studies did not attempt to match heart rate (HR) between the aerobic and resistance exercise. This is most likely attributed to the challenges associated with matching HR during both aerobic and resistance exercise. Thus, following extensive pilot tests, we attempted to match ratings of perceived exertion (RPE) (6–20 Borg scale) (Borg, 1975) between aerobic and resistance exercise. In the aerobic exercise condition, the intensity was set at 40% $\dot{V}O_{2peak}$. Mean HR corresponded to 58.7 ± 6.0% age-predicted maximal HR in the aerobic condition and 52.7 ± 7.5% in the resistance condition. Thus, exercise intensity of the aerobic exercise was considered light according to the ACSM guidelines (Riebe et al., 2018). In the resistance condition, the participants performed resistance exercise using elastic bands (Spoband 55, YKC, Tokyo, Japan). We used elastic bands for the resistance exercise as they are low-cost, portable, have a low risk of injury, and are easily accessible. The findings may be practically useful for exercise prescription at home, or in other settings. The validity of intervention was confirmed by a previous study (Roh et al., 2020). The resistance exercise program was designed to use all major muscle groups (Hofmann et al., 2016). The resistance of the band was 10.3 kg when the length of the band was doubled. The participants performed an exercise program incorporating 42 difference exercises (see **Supplementary Table 1**). This program targeted the following muscle groups: shoulder, chest, back, arms, abdomen, hip, and legs, and included three types of muscle contractions (concentric, eccentric, and isometric) and both multi- and single joint movements. After brief instruction for each program, and participants completed 10 reps of each exercise. The duration of the exercise program was 30 min.

Measurement

Heart rate was recorded continuously using a heart rate monitor (RS800CX; Polar Electro Oy, Kempele, Finland). RPE was recorded before and immediately after exercise. Blood glucose concentration was measured by glucose oxidase method using blood glucose monitor (Glutest Ace, Sanwa Kagaku, Nagoya, Japan). Blood lactate concentration was determined by the lactate oxidase method, using an automated analyzer

(Lactate Pro, Arkray, Kyoto, Japan). Blood sample volume was ∼15 ml for each measurement, and both plasma and serum samples were collected. Plasma samples were obtained from heparinized blood samples by centrifugation at 3,000 rpm for 15 min and stored at −80°C until analysis. Plasma adrenaline and noradrenaline concentrations were determined using a high-performance liquid chromatography system (Shimadzu, Kyoto, Japan). Serum samples were obtained from the venous blood by centrifugation at 3,000 rpm for 15 min and stored at −80°C until analysis. Serum cortisol was measured by commercial radioimmunoassay kit (Immunotech, Marseille, France). Serum IGF-1 concentration was determined using an immunoradiometric assay (IGF-1 IRMA Daiichi, TFB, Tokyo, Japan) and a Wallac 1460 Gamma Counter (Wallac, Turku, Finland). Serum BDNF concentration was measured using the Quantikine Human BDNF Immunoassay (R&D systems, Minneapolis, United States). Due to collection issues resulting in too small sample volumes, the concentration changes of BDNF from two participants (one in the aerobic condition and one in the resistance condition) could not be determined. Adrenaline, noradrenaline, cortisol, IGF-1, and BDNF concentrations were measured at the SRL Clinical Laboratory (Tokyo, Japan). All samples were analyzed in duplicate. Intra- and inter-assay coefficients of variance were 2.8 and 2.6% for adrenaline, 1.0 and 1.4% for noradrenaline, 1.7 and 1.6% for cortisol, and 3.5 and 3.0% for IGF-1.

Data and Statistical Analysis

The distribution of data was assessed using descriptive methods (skewness, outliers, and distribution plots) and inferential statistics (Shapiro-Wilk test). We performed a two-way repeated-measures ANOVA [Exercise Type (aerobic, resistance) × Time (pre, post)] for all variables, followed by Bonferroni-corrected paired *t*-tests for normally distributed data or the Wilcoxon signed rank test for non-normally distributed data. All the RT values were plausible, and within the expected ranges, based on our previous studies (Ando et al., 2013; Komiyama et al., 2015). Effect sizes are presented as partial eta-squared (η_p^2) in the main effects and interactions. Statistical analyses were performed using SPSS (Statistical Package for the Social Sciences) version 25.0 (SPSS Inc., Chicago, IL, United States). We also performed repeated measures correlation analysis (Bakdash and Marusich, 2017; Marusich and Bakdash, 2021) between executive performance (both RT and Accuracy) and peripheral biomarkers. Raincloud plots were created using the JASP version 0.16 (JASP team, Amsterdam, Netherlands). Data are expressed as mean ± SD or median (interquartile range). The significance level was set at $p < 0.05$.

RESULTS

Figure 1 illustrates RT and accuracy of the Go/No-Go task. A significant main effect of Time was observed in RT [$F_{(1,18)} = 5.02$, $p = 0.038$, $\eta_p^2 = 0.22$]; however, no effect of Exercise Type [$F_{(1,18)} = 0.07$, $p = 0.792$, $\eta_p^2 = 0.004$], or interaction [$F_{(1,18)} = 0.06$, $p = 0.812$, $\eta_p^2 = 0.003$] was observed. There were no significant main effects of Exercise Type [$F_{(1,18)} = 0.41$, $p = 0.530$, $\eta_p^2 = 0.02$] and Time [$F_{(1,18)} = 0.01$, $p = 0.939$, $\eta_p^2 = 0.000$] on the accuracy of the Go/No-Go task. However, there was a trend toward a significant interaction effect [$F_{(1,18)} = 4.41$, $p = 0.050$, $\eta_p^2 = 0.20$].

Table 1 summarizes HR, RPE, MAP, and peripheral biomarkers. For HR, we found a significant interaction between Exercise Type and Time, and HR was significantly greater during aerobic exercise than that during resistance exercise ($p = 0.004$). RPE increased after aerobic and resistance exercise. Both adrenaline and noradrenaline increased after both aerobic and resistance exercise, but there were no differences between the modalities (all $p > 0.05$). Glucose significantly decreased after aerobic and resistance exercise (main effect of Time, $p = 0.001$). Although lactate increased after both aerobic ($p = 0.045$) and resistance ($p < 0.001$) exercise, it was higher after resistance exercise ($p < 0.001$). Cortisol decreased after aerobic and resistance exercise (main effect of Time, $p = 0.002$). IGF-1 was elevated following resistance exercise ($p = 0.003$), but not after the aerobic exercise ($p = 0.36$). There was a trend for BDNF to be higher after exercise (main effect of Time, $p = 0.06$).

Table 2 displays the results of repeated measures correlation analysis. Reduction in RT was not associated with changes in any of the circulating biomarkers (all $p > 0.05$). Conversely, accuracy was associated with changes in adrenaline [$r_{rm}(18) = -0.51$, $p = 0.023$], noradrenaline [$r_{rm}(18) = -0.66$, $p = 0.002$], lactate [$r_{rm}(18) = -0.47$, $p = 0.035$], and BDNF [$r_{rm}(17) = -0.47$, $p = 0.044$] in the resistance (**Figure 2**), but not aerobic (all $p > 0.05$), condition.

DISCUSSION

The major findings of this study were: (1) executive performance improved (i.e., reduced RT) after acute RPE-matched aerobic and resistance exercise, while accuracy of the executive task tended to be impaired after resistance exercise; (2) acute physical exercise resulted in alterations in peripheral biomarkers; (3) reduced RT was not correlated with alterations in peripheral biomarkers; and (4) accuracy was associated with increases in peripheral adrenaline, noradrenaline, lactate, and BDNF after resistance, but not aerobic, exercise.

Previous studies using electroencephalogram suggest increases in arousal following both aerobic (Kamijo et al., 2004) and resistance (Tsai et al., 2014) exercise. Acute physical exercise has also been implicated in altering brain circuits involving neurotransmitters (Pontifex et al., 2019; McMorris, 2021). This suggests that executive improvement after acute physical exercise may be related to increased central neurochemical activity. We observed reduced RTs and increases in adrenaline and noradrenaline after both aerobic and resistance exercise. As the increases in both adrenaline and noradrenaline were comparable after aerobic and resistance exercise, it is plausible that the activation of the sympathoadrenomedullary system was also relatively similar following the two types of exercise. Nevertheless, alterations in RTs were not correlated with alterations in peripheral adrenaline and noradrenaline. The

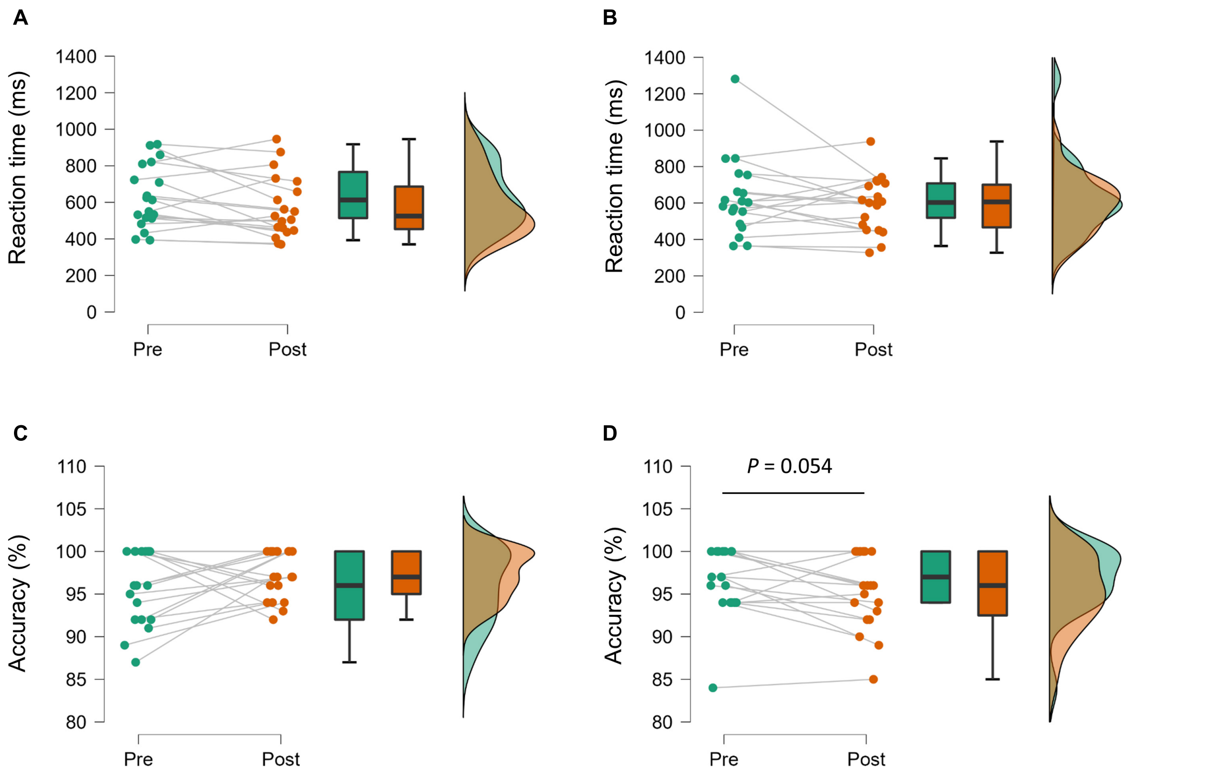

FIGURE 1 | Raincloud plots showing the distribution of reaction time [**(A)** aerobic condition, **(B)** resistance condition] and accuracy of the Go/No-Go task [**(C)** aerobic condition, **(D)** resistance condition]. Plots and lines represent individual data (left). The lower and upper hinges on the boxplots represent the first and third quartile with the median (center). Illustration of data distribution (right).

catecholamine hypothesis describing the exercise-cognition interaction is intriguing (Cooper, 1973). However, the specific mechanism(s) by which acute physical exercise improves executive performance warrant further investigation. We observed a tendency for accuracy to be decreased after resistance exercise (p = 0.054). Furthermore, lower accuracy was associated with a greater increase in peripheral adrenaline and noradrenaline after resistance exercise. Although we did not assess adrenaline and noradrenaline level directly in the brain, excess noradrenaline appears to impair prefrontal cortex function including cognitive function in the brain (Arnsten, 2011). Therefore, the present findings may suggest that greater sympathoexcitation has the potential to be associated with accuracy in a Go/No-Go task.

Executive performance improves during exercise after skipping breakfast (Komiyama et al., 2016), which suggests that energy substrates may compensate for reduced availability of blood glucose. It is possible that lactate is used by the brain (Quistorff et al., 2008), and increases in blood lactate concentration appear to provide energy that contributes to improvements in attentional and executive performance after high intensity exercise (Tsukamoto et al., 2016; Hashimoto et al., 2018; Herold et al., 2022). Conversely, Coco et al. (2009, 2020) have shown that increase in blood lactate concentration have adverse effects on attentional and executive performances. We observed no associations between reduction in RT and alterations in lactate or glucose. The findings are inconsistent with others (Tsukamoto et al., 2016; Hashimoto et al., 2018; Herold et al., 2022). It is likely that these heterogeneous findings are attributable to methodological differences. First, the exercise intensity was higher (high intensity interval exercise: 80—90% and 50–60% of maximal workload) in previous studies (Tsukamoto et al., 2016; Hashimoto et al., 2018), compared to the intensity used in the current study (40% $\dot{V}O_{2peak}$). Given that blood lactate substantially increases after high intensity, contribution of blood lactate to cognitive improvement after acute physical exercise may be dependent on the degree of increase in blood lactate. Second, Hashimoto et al. (2018) directly measured brain blood lactate uptake, while blood lactate was measured from the antecubital vein in the present study. This may also explain the lack of a significant correlation between executive improvement and increase in blood lactate.

In the resistance condition, the trend toward impaired accuracy was modestly associated with blood lactate. Blood lactate uptake in the brain becomes significantly elevated when arterial lactate increases, for instance, in response to strenuous physical exercises (Quistorff et al., 2008). In the present study, increases in blood lactate was limited up to around 3 mmol L^{-1} in most cases. Hence, the amount of blood lactate uptake in

TABLE 1 | Heart rate (HR), MAP, and peripheral biomarkers before and after acute aerobic and resistance exercise.

Variable	Aerobic		Resistance		*P*-value		
					Main effect		Interaction
	Pre	Post	Pre	Post	Exercise type	Time	
HR, bpm	70 ± 5	116 ± 12***	67 ± 14	104 ± 14*** ##	$F_{(1,18)} = 7.20$, $p = 0.015$, $\eta_p^2 = 0.29$	$F_{(1,18)} = 355.16$, $p < 0.001$, $\eta_p^2 = 0.95$	$F_{(1,18)} = 8.52$, $p = 0.009$, $\eta_p^2 = 0.32$
RPE	6 (6–7)	12 (10–13)	6 (6–7)	13 (11–13)	$F_{(1,18)} = 2.77$, $p = 0.114$, $\eta_p^2 = 0.13$	$F_{(1,18)} = 345.20$, $p < 0.001$, $\eta_p^2 = 0.95$	$F_{(1,18)} = 3.09$, $p = 0.096$, $\eta_p^2 = 0.15$
MAP, mmHg	88 ± 4	88 ± 8	88 ± 8	86 ± 8	$F_{(1,18)} = 0.75$, $p = 0.398$, $\eta_p^2 = 0.04$	$F_{(1,18)} = 0.67$, $p = 0.423$, $\eta_p^2 = 0.04$	$F_{(1,18)} = 1.27$, $p = 0.275$, $\eta_p^2 = 0.07$
Adrenaline, pg/mL	37 ± 14	69 ± 23	27 (18–59)	59 ± 28	$F_{(1,18)} = 1.32$, $p = 0.226$, $\eta_p^2 = 0.07$	$F_{(1,18)} = 98.89$, $p < 0.001$, $\eta_p^2 = 0.85$	$F_{(1,18)} = 1.88$, $p = 0.187$, $\eta_p^2 = 0.10$
Noradrenaline, pg/mL	351 ± 90	523 ± 170	377 ± 147	548 (437–674)	$F_{(1,18)} = 2.19$, $p = 0.156$, $\eta_p^2 = 0.11$	$F_{(1,18)} = 23.31$, $p < 0.001$, $\eta_p^2 = 0.56$	$F_{(1,18)} = 0.65$, $p = 0.430$, $\eta_p^2 = 0.04$
Glucose, mg/dL	83 ± 6	80 ± 7	84 ± 8	81 ± 7	$F_{(1,18)} = 0.40$, $p = 0.538$, $\eta_p^2 = 0.02$	$F_{(1,18)} = 14.70$, $p = 0.001$, $\eta_p^2 = 0.45$	$F_{(1,18)} = 0.05$, $p = 0.822$, $\eta_p^2 = 0.003$
Lactate, mmol/L	1.1 ± 0.3	1.2 (1.1–1.4)*	1.1 (1.0–1.2)	2.8 (2.3–3.2)*** ###	$F_{(1,18)} = 48.57$, $p < 0.001$, $\eta_p^2 = 0.73$	$F_{(1,18)} = 102.62$, $p < 0.001$, $\eta_p^2 = 0.85$	$F_{(1,18)} = 36.59$, $p < 0.001$, $\eta_p^2 = 0.67$
Cortisol, μg/mL	15 ± 5	11 (10–15)	16 ± 5	12 (9–19)	$F_{(1,18)} = 1.18$, $p = 0.292$, $\eta_p^2 = 0.06$	$F_{(1,18)} = 13.31$, $p = 0.002$, $\eta_p^2 = 0.43$	$F_{(1,18)} = 0.008$, $p = 0.932$, $\eta_p^2 = 0.000$
IGF-1 ng/mL	211 ± 56	209 ± 51	203 ± 45	213 ± 40**	$F_{(1,18)} = 0.10$, $p = 0.752$, $\eta_p^2 = 0.01$	$F_{(1,18)} = 3.48$, $p = 0.079$, $\eta_p^2 = 0.16$	$F_{(1,18)} = 12.10$, $p = 0.003$, $\eta_p^2 = 0.40$
BDNF, pg/mL	27,465 ± 6,281	28,694 ± 7,099	29,094 ± 5,695	29,988 ± 7,488	$F_{(1,16)} = 1.67$, $p = 0.215$, $\eta_p^2 = 0.09$	$F_{(1,18)} = 3.98$, $p = 0.063$, $\eta_p^2 = 0.20$	$F_{(1,18)} = 0.069$, $p = 0.796$, $\eta_p^2 = 0.004$

Values are mean ± standard deviation or median (interquartile range).
$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$ vs. pre. $^{\#\#\#}p < 0.001$, $^{\#\#}p < 0.01$ vs. aerobic exercise.
HR, heart rate; RPE, ratings of perceived exertion; MAP, mean arterial pressure; IGF-1, Insulin-like growth hormone factor 1; BDNF, Brain-derived neurotrophic factor.

TABLE 2 | Repeated measures correlation between cognitive performance (reaction time and accuracy) and peripheral biomarkers.

Variable	Aerobic		Resistance	
	Reaction time	Accuracy	Reaction time	Accuracy
Adrenaline	$r_{rm}(18) = -0.25$, $p = 0.285$	$r_{rm}(18) = 0.24$, $p = 0.31$	$r_{rm}(18) = -0.36$, $p = 0.118$	$r_{rm}(18) = -0.51$, $p = 0.023$*
Noradrenaline	$r_{rm}(18) = -0.30$, $p = 0.199$	$r_{rm}(18) = 0.11$, $p = 0.641$	$r_{rm}(18) = 0.15$, $p = 0.533$	$r_{rm}(18) = -0.66$, $p = 0.002$**
Glucose	$r_{rm}(18) = -0.12$, $p = 0.606$	$r_{rm}(18) = -0.28$, $p = 0.224$	$r_{rm}(18) = -0.10$, $p = 0.67$	$r_{rm}(18) = 0.21$, $p = 0.383$
Lactate	$r_{rm}(18) = -0.24$, $p = 0.303$	$r_{rm}(18) = 0.28$, $p = 0.236$	$r_{rm}(18) = -0.18$, $p = 0.437$	$r_{rm}(18) = -0.47$, $p = 0.035$*
Cortisol	$r_{rm}(18) = 0.12$, $p = 0.605$	$r_{rm}(18) = 0.00$, $p = 0.996$	$r_{rm}(18) = -0.12$, $p = 0.616$	$r_{rm}(18) = 0.28$, $p = 0.229$
IGF-1	$r_{rm}(18) = -0.19$, $p = 0.423$	$r_{rm}(18) = 0.03$, $p = 0.912$	$r_{rm}(18) = -0.07$, $p = 0.762$	$r_{rm}(18) = -0.40$, $p = 0.081$
BDNF	$r_{rm}(17) = -0.24$, $p = 0.332$	$r_{rm}(17) = 0.33$, $p = 0.163$	$r_{rm}(17) = -0.01$, $p = 0.956$	$r_{rm}(17) = -0.47$, $p = 0.044$*

$^{**}p < 0.01$, $^{*}p < 0.05$.

the brain is presumably minimal, and it is less likely that blood lactate directly impaired the accuracy. Our findings suggest that there is a large inter-individual variability in accuracy of a task probing executive functioning after acute resistance exercises (see **Figure 1D**). Furthermore, accuracy seems to be more impaired in individuals who showed more pronounced physiological alterations (i.e., higher level of peripheral blood lactate) in response to an acute bout of resistance exercises (see also **Figure 2C**). In general, the latter finding fits to the observations of Coca and colleagues who reported that high levels of lactate have detrimental effects on attentional and executive performance (Coco et al., 2009, 2020). However, given the inconclusive results

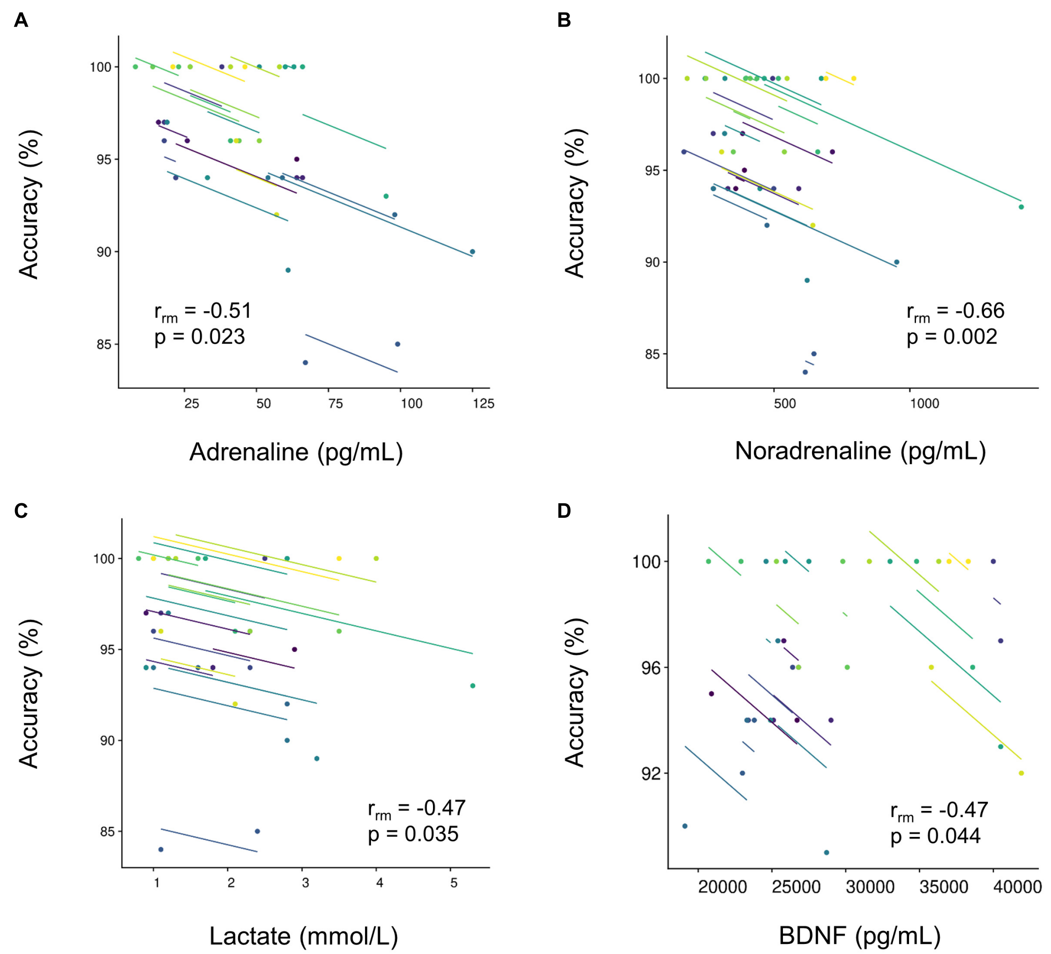

FIGURE 2 | Repeated measure correlations between the accuracy of the Go/No-Go task and peripheral circulating biomarkers [**(A)** adrenaline, *n* = 19; **(B)** noradrenaline, *N* = 19; **(C)** lactate, *N* = 19; and **(D)** brain-derived neurotrophic factor, *N* = 18] in the resistance condition. Plots represent individual data. Lines show the r_{rm} fit for the participants. Same colors represent data from the same participants.

in the literature, further studies are warranted to investigate whether lactate acts as a possible mediator of exercise-induced changes in executive performance.

The HPA system is sensitive to acute physiological stress including exercise (Gaffey et al., 2016; Williams et al., 2019). In the present study, cortisol decreased after both aerobic and resistance exercise. Hill et al. (2008) reported that low intensity aerobic exercise (i.e., 40% maximal oxygen uptake) decreased circulating cortisol level (Hill et al., 2008). Tsai et al. (2014) also reported decrease in cortisol level after moderate resistance exercise (Tsai et al., 2014). The present results are in line with these observations. We observed no association between executive improvement and in the change in cortisol after acute aerobic or resistance exercise. Tsai et al. (2014) suggested that arousal level might be modulated by alteration in cortisol. However, alterations in cortisol were not associated with alterations in executive performance. These findings suggest cortisol may not be directly associated with executive performance after acute physical exercise.

Consistent with the literature acute resistance, but not aerobic, exercise increased peripheral IGF-1 (Rubin et al., 2005; Rojas Vega et al., 2010; Tsai et al., 2014; Tsai et al., 2018). BDNF also tended to increase after both aerobic and resistance exercise. Although this is not always the case, previous studies have reported that BDNF increases after exercise at higher intensities (Ferris et al., 2007; Winter et al., 2007). Therefore, given the relatively low exercise intensity of the present study, the absence of significant increases in BDNF are perhaps not surprising. We observed no association between executive performance and alterations in IGF-1 and BDNF. Previous studies reported no association between alterations in IGF-1 and executive performance after acute resistance exercise (Tsai et al., 2014, 2018). Similarly, increases in IGF-1 after exhaustive exercise have previously been shown to be unrelated with executive performance (Sudo et al., 2017) and alterations in BDNF were not associated with executive performance and neurophysiological variables after acute physical exercise (Tsai et al., 2016). In contrast, significant associations were observed between alteration in BDNF and performance in executive and memory tasks after acute physical exercise (Winter et al., 2007; Lee et al., 2014; Skriver et al., 2014). Thus, although alterations in BDNF appears not to be directly associated with improvement in executive performance after acute physical exercise, BDNF may contribute to memory performance. Given that IGF-1 and BDNF are associated with angiogenesis, synaptogenesis, and neurogenesis after long-term exercise (Cotman and Berchtold, 2002; Voss et al., 2011; Nieto-Estevez et al., 2016), it is reasonable to think that alterations in IGF-1 or BDNF may play a minor role in executive performance following acute physical exercise. Nevertheless, further studies are required to clarify the contribution of IGF-1 and BDNF to cognitive performance (e.g., memory performance) after acute physical exercise. In the resistance condition, the trend toward an impairment in accuracy was moderately associated with BDNF. Previous studies indicated that increase in BDNF is dependent on exercise intensity (Ferris et al., 2007; Winter et al., 2007). Thus, like the association between impaired accuracy and blood lactate, accuracy could be more impaired in those individuals showing more pronounced alterations in specific biomarkers in response to a given exercise intensity.

The present study was not without limitation. First, despite attempting to match exercise intensity between the aerobic and resistance exercise, there were significant differences in HR (∼12 beats min^{-1}). We also found inter-individual differences in HR across both conditions. Second, we observed a trend toward an impairment in accuracy and the association between accuracy and peripheral biomarkers only in the resistance condition. Given that dose-response is important to examine exercise-cognition interaction (Herold et al., 2019, 2020), the results may be attributable to these differences in relative exercise intensity. Third, since we did not include a control condition, we cannot rule out the possibility that time-related factors including practice effects and circadian change of peripheral biomarkers. However, the participants were familiarized with the cognitive task and exercise duration was only 30 min. Thus, the effects may be small, if any. Fourth, we estimated sample size based on the primary outcome (i.e., RT). This might lead to low statistical power to detect the association between cognitive performance and peripheral biomarkers. Indeed, we observed no significant correlations between the reductions in RTs and peripheral biomarkers following acute aerobic and resistance exercise. The present results suggest that these peripheral circulating biomarkers are not capable of indicating the level of executive performance after exercise. However, the effects of acute physical exercise on cognitive performance are multifaceted and probably determined by the integration of several physiological factors. Perhaps, some of these peripheral biomarkers may contribute to executive improvement in a synergistic manner. Fifth, we did not take consider the impact of other potential confounding factors including nutritional status, habitual physical activity, and psychological factors (e.g. motivation, concentration, and fatigue). Finally, we collected venous and capillary blood samples immediately after aerobic and resistance exercise. The timing of the measurement is commonly used in the literature. However, concentrations of peripheral biomarkers appear to change depending on the time elapsed after physical exercises (e.g., Griffin et al., 2011; Gregory et al., 2013; Hashimoto et al., 2018), and the association between executive performance and peripheral biomarkers are likely to be influenced by the timing of measurement (e.g., immediately or 15 min after exercise). This should be considered in future studies.

CONCLUSION

In conclusion, despite observing a reduction in RT in the Go/No-Go task following both aerobic exercise and resistance exercise, we observed no significant correlations between these reductions and peripheral adrenaline, noradrenaline, glucose, lactate, cortisol, IGF-1, or BDNF. These results suggest that alterations in these peripheral circulating biomarkers do not directly contribute to improved RT after aerobic and resistance exercise. However, greater sympathoexcitation, reflected by greater increase in noradrenaline, may be associated with a tendency for a reduction accuracy after acute resistance exercise.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of Fukuoka University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SA and TK contributed to the conception and design of the study and drafted the manuscript. SA, TK, YT, and MS acquired the data and performed the data analysis. JC, YU, and YH edited and revised the manuscript. All authors interpreted the results, read, and approved the final version of the manuscript.

FUNDING

This study was supported in part by a grant from Descente and Ishimoto Memorial Foundation for Promotion of Sports Science and the Japan Society for the Promotion of Science KAKENHI (Grant Number: 16H03230).

ACKNOWLEDGMENTS

We acknowledge Hiroaki Tanaka for his support. We are also grateful to Kisou Kubota for providing software to assess cognitive performance, and to Kenji Ando for data acquisition.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnbeh.2022.853150/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 08 April 2022
doi: 10.3389/fnbeh.2022.822199

COVID-19 Quarantine Impact on Wellbeing and Cognitive Functioning During a 10-Week High-Intensity Functional Training Program in Young University Students

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

Received: 25 November 2021
Accepted: 10 March 2022
Published: 08 April 2022

Citation:
Ballester-Ferrer JA, Carbonell-Hernández L, Pastor D and Cervelló E (2022) COVID-19 Quarantine Impact on Wellbeing and Cognitive Functioning During a 10-Week High-Intensity Functional Training Program in Young University Students.
Front. Behav. Neurosci. 16:822199.
doi: 10.3389/fnbeh.2022.822199

Physical exercise can improve cognitive functioning and wellbeing; however, the degree of change in either of these two variables seems to be related to the exercise intensity or type. Therefore, new physical training (PT) programs have been developed to increase exercise efficiency. One such example is high-intensity functional training (HIFT), which has proven to be a time-efficient and highly effective strategy to improve physical fitness. This study analyzed whether HIFT can affect reaction time (RT) and vitality, as well as positive and negative affect. Forty-two college students participated in the study, 21 in the experimental group and 21 in the control group. The experimental group completed 10 weeks of training, five of which were supervised, and the remainder consisted of online training during the COVID-19 quarantine. Participants were evaluated at the beginning, at the end of the 5 weeks of supervised training, and after the 5 weeks of online training. HIFT improved RT without changes in psychological wellbeing during the entire period of training supervised and online. Therefore, during the HIFT program, the quarantine situation did not adversely affect this population's wellbeing, but it did negatively affect adherence to the training program.

Keywords: reaction-time, exercise, COVID-19, wellbeing, HIFT, quarantine

INTRODUCTION

It is well-known that acute and chronic physical exercise (PE) affects physical and physiological functions and influences aspects related to cognitive functioning. According to Herold et al. (2019), it is crucial to distinguish between physical activity (PA), acute and chronic PE, and physical training (PT). All muscle activity that increases energy expenditure is PA (Herold et al., 2019). PE is a specific, planned and structured PA. PE may include a single bout (acute PE) or repeated bouts over a short-term or long-term period (chronic PE). Finally, when chronic PE is purposed to increase (or maintain) one or multiple dimensions of fitness, this is known as PT (Herold et al., 2019).

Regarding exercise and cognitive functioning, PA and fitness have been linked to the academic performance of young students (Marques et al., 2018), inhibitory function in young and old subjects (Peruyero et al., 2017; Carbonell-Hernández et al., 2019; Pastor et al., 2019), memory (Erickson et al., 2011; Jeon and Ha, 2017), wellbeing (Cervelló et al., 2014), depression (McMahon et al., 2017), and other cognitive outputs. However, it is not well-known how different variables of the exercise session (e.g., exercise intensity, exercise duration, exercise type) can modulate it. The literature on exercise and cognition has traditionally dealt with non-modifiable parameters like sex or genotype. Less research is available on the modifiable parameters, like the individual dose-response relationship (Herold et al., 2019).

Regarding the dose-response relationship of exercise to improve cognitive functioning and wellbeing, it is clear that exercise intensity does matter. According to wellbeing, low-intensity but not high-intensity aerobic exercise seems more effective in producing acute changes in wellbeing in adolescents (Pastor et al., 2019). However, high-intensity chronic exercise in university students is more efficient in reducing stress and improving wellbeing (Leuchter et al., 2022).

Regarding cognitive functioning, high-intensity aerobic exercise seems to produce greater improvements in other age groups and different cognitive domains like choice reaction time (RT) (Chang et al., 2012). Furthermore, in favor of high-intensity acute exercise, it has been shown that high intensity can produce greater increases in neurotrophins like brain-derived neurotrophic factor (BDNF) (Saucedo Marquez et al., 2015). BDNF promotes neurogenesis, synaptic plasticity, dendritic and axonal growth, and cell survival (Walsh et al., 2020). The BDNF increase with exercise intensity may be related to lactate release (Ferris et al., 2007). It is well-known that high-intensity exercise performance produces a considerable release of lactate (Ferguson et al., 2018), and high-intensity functional training (HIFT) implies high-intensity exercise. Moreover, lactate release is also related to cerebral blood flow and improves neurogenesis, neuroprotection, neuronal plasticity, and memory (Hashimoto et al., 2021).

Moreover, resistance training can also improve cognitive functioning (Landrigan et al., 2020); single bouts of resistance exercise showed more significant improvements when higher loads were used (Chang and Etnier, 2009). However, the optimal exercise and training characteristics to effectively enhance cognitive functioning with chronic PE programs are relatively unknown (Soga et al., 2018). So, it seems that a single bout of both high-intensity aerobic or resistance exercise can acutely improve RT. However, we do not know if high-intensity exercise would also be effective when applied in chronic PE programs. It is possible that continuous exposure to lactate, in turn, could induce the release of BDNF to produce such an effect (Hashimoto et al., 2021).

Regarding changes in cognitive functioning, PT and acute PE have been shown to improve attention processes, information processing speed, and executive control (Colcombe and Kramer, 2003; Tsai et al., 2014; Pontifex et al., 2015). Among the various tools generally used to determine the impact of PE on the above-mentioned cognitive variables, RT has been used in the literature to evaluate cognitive and motor functions, as it involves both central and peripheral components (Ozyemisci-Taskiran et al., 2008). RT is understood as the time a person needs to initiate a movement (Magill, 2010). There are different types of RT. On the one hand, simple RT occurs when only one possible stimulus requires a single type of response (Posner and McLeod, 1982), whereas in more complex choice RT, there are different possibilities to choose from during the experiment, as it involves the appearance of different stimuli that require different responses (Neubauer, 1990). More specifically, RT measures processing speed (Mulder and van Maanen, 2013), and this variable reflects a person's cognitive functioning (Deary et al., 2010). At the morphological level, processing speed may be an indirect measure of white brain substance, as changes in this substance are associated with changes in processing speed (Gunning-Dixon et al., 2009). At the behavioral level, it has recently been shown that medical students with better academic performance had lower RT (Prabhavathi et al., 2017). Not only that, in middle-aged and older people, lower performance in RT tasks can be a predictor of heart disease and stroke mortality (Shimizu et al., 2018).

Like in cognition, PA can improve wellbeing in young students (McMahon et al., 2017). Nowadays, wellbeing is a European priority (Miret et al., 2015), but there is no clear consensus about its definition or operationalization (Korhonen et al., 2014). Positive or negative indicators such as self-esteem, quality of life, positive and negative affect or vitality are usually used (Pastor et al., 2019). Some authors consider two perspectives for studying wellbeing: the hedonic perspective, which considers wellbeing as the presence of positive affect and the absence of negative affect; and the eudaimonic perspective, which associates wellbeing with the possibility of performing or expressing the most valuable human potentials, related to optimal psychological functioning (Ryan et al., 2013). Moreover, in both young and older individuals, it has been seen that cognitive performance changes could be affected by aspects such as mood and social relations (Lieberman et al., 2014). In addition, cardiorespiratory fitness (CRF) is related to vitality in young people (Eddolls et al., 2018), and vitality should correlate with positive and negative affect (Cervelló et al., 2014). Thus, the improvement of CRF with exercise training could improve wellbeing.

Consequently, it would be interesting to determine how PE can affect wellbeing and processing speed. At the acute level, improvements have been reported in complex RTs after sub-maximum exercise in university students (Audiffren et al., 2008; Ashnagar et al., 2015) and in adolescents' wellbeing (Pastor et al., 2019). On the other hand, some studies have observed a relationship between fitness and RT in young students (Luque-Casado et al., 2013; Wang et al., 2015; Maghsoudipour et al., 2018), although others did not find this association (Moradi et al., 2019). At the chronic level, the effects of the exercise intensity, duration, and frequency to produce long-term effects on processing speed and wellbeing in this population are not well-established.

Regarding exercise programs, the need to investigate new training methods to improve several fitness components simultaneously and efficiently, without high volumes of training and favoring adherence, has been indicated previously (Heinrich et al., 2014). In this sense, HIFT has recently emerged. HIFT is defined as a training style that incorporates various functional movements performed at high exercise intensity and is designed to improve general physical fitness and performance parameters (Feito et al., 2018). Unlike HIIT, this type of training combines aerobic activities with exercises to improve muscle strength (Feito et al., 2018). Among its benefits are improved body composition, power, muscle strength, and aerobic capacity, the same as or even more so than when performing continuous workouts or HIIT (Feito et al., 2018). However, the term "functional" may not be correct in this training style (Ide et al., 2021), as HIFT can be more clearly described as combined or concurrent training. Therefore, like a high-intensity aerobic and resistance-training regime, it seems a powerful candidate to improve RT and wellbeing in young people. Moreover, high-intensity exercise can release high amounts of lactate, a molecule positively related to cognitive function (Hashimoto et al., 2021).

Therefore, this study's main objective was to determine whether a supervised HIFT group program of 10 weeks could improve processing speed and wellbeing. However, as a consequence of the COVID-19 pandemic, a national lockdown was announced in the middle of the program (week five), and supervised training had to be terminated. Thus, online training was implemented for the next 5 weeks.

The COVID-19 pandemic impacted the economy and society in many aspects, disturbing lifestyle and health behaviors (Dragun et al., 2021). The lockdown deteriorated daily activities, especially physical activities (Dragun et al., 2021). In addition, as a consequence of the quarantine, there was a negative impact on the population's wellbeing (Brooks et al., 2020), with higher levels of anxiety and depression (Burke et al., 2020).

The study's second objective arose as a consequence of the COVID-19 quarantine. We aimed to determine whether the "stay-at-home" orders and the need to continue training at home individually, adapting it to the new situation, would impact cognitive functioning and wellbeing in the participants.

Thus, we hypothesized that the 5-week HIFT supervised training phase would improve participants' RT and psychological wellbeing and give rise to high adherence rates. Conversely, the phase carried out during the 5 weeks of strict quarantine due to COVID-19 was expected to decrease wellbeing compared to the in-person, supervised program, coupled with lower adherence and a reduction in RT improvement.

MATERIALS AND METHODS

Participants

The sample consisted of 42 college students, 21 in the experimental group (14 males and 7 females) and 21 in the control group (9 males and 12 females). All the participants were adults over 18 years old, and all of them claimed to be sedentary (one or fewer days of PE a week) during at least the last 6 months. In addition, all participants completed an initial questionnaire to ensure they met the requirements to be part of the study, such as not having recently suffered injuries and not being involved in any other training program. Their sociodemographic characteristics are summarized in **Table 1**.

TABLE 1 | Anthropometric and fitness characteristics of the participants (N = 42).

Characteristics	Experimental (n = 21)	Control (n = 21)
Age (years)	19.71 ± 1.71	21.52 ± 2.74
Weight (kg)	69.17 ± 8.04	66.57 ± 13.57
Height (m)	1.72 ± 0.09	1.69 ± 0.08
BMI (kg/m^2)	23.20 ± 2.25	23.20 ± 3.73
VO_2 max (ml kg^{-1}min^{-1})	43.50 ± 5.42	
MAS (km/h)	14.20 ± 1.75	15.47 ± 2.91
HR max (beats min^{-1})	200.90 ± 7.99	193.60 ± 8.16

All values are expressed as mean ± SD. BMI, body mass index; VO_2 max, maximum oxygen consumption; HR max, maximum heart rate; MAS, maximal aerobic speed.

Measurements

Cardiorespiratory Function: Stress Test

Participants of the experimental group performed a maximum incremental test on a treadmill with a measure of oxygen consumption (VO_2) and heart rate (HR) throughout the test to determine the maximum VO_2 (VO_2 max), maximum HR (HR max), and their associated values in the first (VT1) and second ventilatory threshold (VT2). The exchange of respiratory gases was measured using the MasterScreen CPX analyzer (Hoechberg, Germany) breath by breath after being calibrated. The VO_2 max was calculated as the highest 30-s mean of VO_2. In addition, 15-s means of O_2 and CO_2 were used to determine VT1 and VT2 (Pettitt et al., 2013). Participants were not allowed to drink or speak during the test and were asked to refrain from intense exercise 24 h earlier.

The incremental test protocol consisted of a 3 min warm-up at 5 km/h with a 1% slope. Then, the test was performed on a 1% slope and began at a speed of 6 km/h and increased 1 km/h per minute until fatigue.

The incremental test protocol could not be repeated at the end of the study due to the COVID-19 lockdown, so no data regarding the possible fitness improvements of the participants was obtained.

Cognitive Functioning

Reaction Time

A test of increasing difficulty was used to measure the time required to respond to a stimulus. All the participants were requested to complete the test in the afternoon at home. The test was carried on a day with no exercise training session in a quiet place. A digital application with three tests was used in the study (AppAndAbout, 2019). Each test consisted of passing ten trials of different stimuli, and between each trial, there was a random rest period between 1,000 and 1,500 ms. The first test, the Training Test (TrT), was used to train the participants at the beginning of each measure. In the TrT, a green or red luminous stimulus was presented, and the subject had to press a green button only if the stimulus presented was of the same color. In the second test, the Choice Reaction Test (CRT) (ICC = 0.78, SEM = 0.05 s), there were also two luminous signals, red and green, and two buttons, red and green. The subject had to press the button with the matching color corresponding to the luminous signal presented (e.g., if the light signal was red, they had to press the red button). The third test, the Interference Test (InT) (ICC = 0.80, SEM = 0.05 s), consisted of introducing interference in the decision process of the second test: the participants had to respond in reverse, such that the signal should not coincide with the color of the button (e.g., if the light signal was green, they must press the red button). The third test was the most complex because it added interference. A familiarization protocol was used at the beginning of the study, repeating all tests five times. The familiarization protocols of the first 15 participants were analyzed to calculate the ICC of the tests, with moderate to strong reliability (Wells et al., 2014).

Psychological Wellbeing

Subjective Vitality

The Subjective Vitality Questionnaire (Ryan and Frederick, 1997) was used to measure the perception of vitality before and after the two phases of the training program, adapted to Spanish by Molina-García et al. (2007). This questionnaire can be considered a measure of psychological wellbeing (Ryan et al., 2013). This instrument comprises seven items that indicate how one feels at present (e.g., I feel alive and vital). The responses are rated on an eight-point Likert-type scale ranging from 0 (*not completely true*) to 7 (*very true*). Cronbach's alpha in the different experimental situations was comprised between 0.88 and 0.95.

Affective State

Following each training program phase, participants were asked to complete the *Positive and Negative Affect Schedule* (Mackinnon et al., 1999), which assesses their positive and negative feelings. This questionnaire is considered a hedonic measure of wellbeing. The scale is made up of nine adjectives, which are grouped into two factors in response to the item "Indicate how you feel right now...." Four of its items are associated with *Positive Affect* ("joyful, happy, content, amused") and five with *Negative Affect* ("depressed, worried, frustrated, angry, unhappy"). The responses are rated on an eight-point Likert-type scale ranging from 1 (*not completely*) to 7 (*extremely*). Cronbach's alpha for Positive Affect was between 0.89 and 0.95, and for Negative Affect between 0.83 and 0.92.

Adherence to the Training Program

Participation was monitored through a registration sheet in the supervised sessions and a mobile application during the quarantine phase. In addition, each person recorded the session and their perception of effort (RPE: rate of perceived exertion) 30 min after completing the session by the modified RPE-10 scale. A total of 30 sessions was performed, 15 in each of the phases of the program (supervised and online phases). Adherence was considered sufficient if at least 90% of the sessions were completed (Heinrich et al., 2014).

Procedure

The physical evaluation was carried out at the beginning of the program, and RT and wellbeing evaluations were conducted before the start of the training program (January–February 2020), after 5 weeks of the supervised group intervention (March 2020), and after 5 weeks of individual training during the quarantine period due to the COVID-19 global pandemic (April 2020). The experimental procedure for this study followed the latest (7th) Helsinki Declaration and was approved by the University Ethics Committee (UMH.CID.DPC.02.17). Study participants gave their informed written consent before participating in the study and were informed of the confidentiality and anonymity of the results obtained.

The participants' experimental allocation was distributed as is shown in the CONSORT flow chart (**Figure 1**). The inclusion criteria were (a) did not participate in any PE program simultaneously, (b) physical inactivity in the last 6 months, and (c) did not suffer injuries in the last 6 months. The participants were randomized using Microsoft Excel software with the "Random" function. There was no allocation concealment.

The sample size was calculated *post-hoc* using G-Power (G*Power software, ver. 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany).[1] It was calculated for the RT analysis. For an ANOVA-RM 2 × 3, and with 42 participants, it is necessary an effect size of $\eta_p^2 > 0.04$ to ensure a statistical power $(1-\beta) > 0.8$ ($\alpha = 0.05$, correlation among repetitive measures = 0.45). Results have a positive power with $\eta_p^2 > 0.04$.

Training Program

Two research group members prescribed the supervised training program and carried it out. The sessions were 1 h long, 3 days a week (Monday, Wednesday, and Thursday). The sessions were conducted at university facilities, dividing the participants into two different time schedules to ensure the availability of the material. The training sessions during the quarantine phase were sent to participants *via* a mobile application to be performed at home.

The sessions were divided into four parts: (a) 10 min of a standardized warm-up; (b) a strength-block of about 15 min, occasionally, on a specific movement pattern with load requirements as a function of the manifestations of muscular endurance or hypertrophy depending on the week; (c) HIFT as the primary training block, which ranged from 10 to 30 min; and (d) cool down through mobility exercises and 10 min of static stretches. Repetition methods (completing a series of exercises in the shortest possible time, or maximum repetitions in a scheduled time) or time methods (rest-work ratios similar to the traditional HIIT method) were used in the main HIFT block. This block included cyclic exercises, such as running or jumping rope, and muscle endurance exercises with bodyweight or light loads (e.g., squats, swings, med ball throws, push-ups, pull-ups, jumps, and more) (Feito et al., 2018). The exercise intensity was all-out for all, and the recovery was self-paced, self-selected, and passive (Feito et al., 2018). The training sessions were adapted to the new situation during the quarantine period. Thus, work with loads was prescribed using generic materials that anyone may have at home (bags of rice, bottles of water, milk containers, and other common materials) (Jiménez-Pavón et al., 2020). The days and hours of training were the same during the presential and quarantine periods.

[1] http://www.gpower.hhu.de/

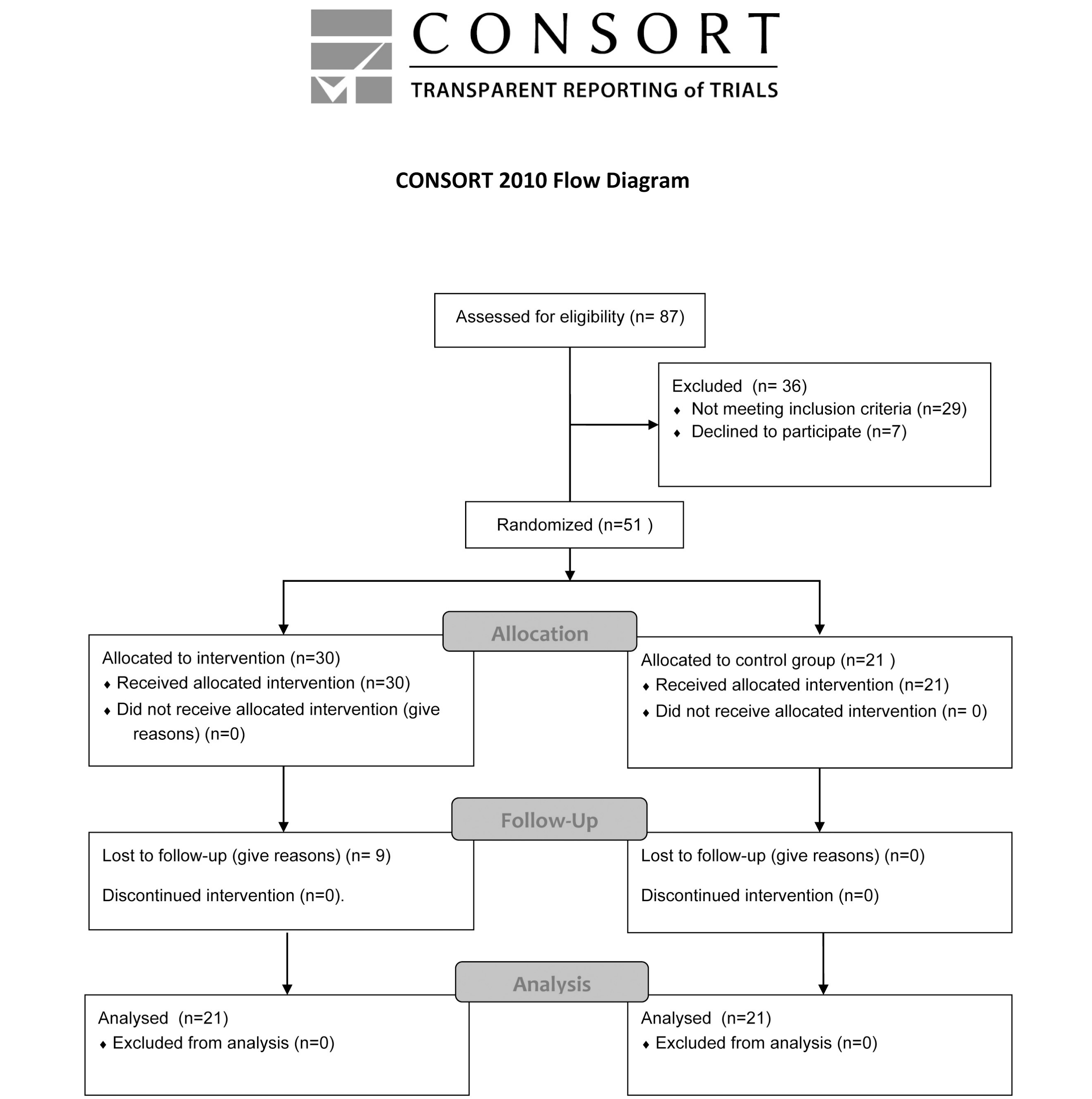

FIGURE 1 | Consort flow chart.

Monitoring and Quantification of Training

The exercise intensity of the presential training sessions was rated with two different methods, one objective and one subjective: HR and subjective RPE-10 scale of the session. Only RPE was used during the sessions during quarantine.

Heart rate was registered during the sessions with the Polar Team2 Pro System (Polar Electro Oy, Kempele, Finland), which includes 20 coded chest straps, allowing HR registration every second. The recorded HR was used to calculate a load of each session, using Lucia's Training Impulse (TRIMPs) method (Lucía et al., 1999), which uses the HR at the individual ventilatory thresholds obtained in the stress test to establish three training zones: Zone 1 "below VT1," Zone 2 "between VT1 and VT2," and Zone 3 "above VT2." For the calculation of the TRIMP, the time expended in each zone is multiplicated by the zone number (1, 2, or 3).

The modified 10-point scale was used to quantify the internal load through the RPE (Foster et al., 2001). Participants were asked to determine the exercise intensity of the training 30 min after completing it.

Statistical Analysis

Repeated-measures ANOVA was performed, followed by a *post-hoc* test with Bonferroni adjustment to detect changes between the different time measurements for CRT, InT, positive affect, negative affect, vitality, and attendance. The bilateral significance level was set at $p < 0.05$. Sphericity was evaluated with Mauchly's sphericity test. The effect sizes are expressed as partial eta-squared ($\eta_p{}^2$) and are grouped as small (≤0.01), medium (≤0.06), and large (≤0.14) (Cohen, 1992). Paired *t*-test were used to analyze the exercise intensity of the sessions. A Pearson correlation was performed to analyze the relations of the wellbeing questionnaires. The results were analyzed with JASP 0.16 software (Eric-Jan Wagenmakers, Department of the Psychological Methods University of Amsterdam, Nieuwe Achtergracht 129B, Amsterdam, Netherlands).

RESULTS

Perception of effort was maintained with similar values during the online training sessions and the supervised training sessions (**Figure 2**). Moreover, during the supervised training sessions, the evolution of RPE was similar to LuTRIMP evolution (**Figure 2**). Despite changes in the structure of the sessions between the two phases, no significant differences in the exercise intensity of the sessions were observed through the recording of RPE between the supervised sessions and online sessions or between sessions (**Figure 2**), analyzed with paired *t*-tests ($p = 0.39$). Therefore, the stabilization of improvements in RT and the decrease in adherence between the two phases of the program were not attributable to load differences in the prescribed sessions, so there may be other underlying factors.

The repeated-measures ANOVA shows the interaction between TIME at the three time points [pretest (PRE), after 5 weeks of supervised training (POST 5), and after 5 weeks of online training (POST 10)] and GROUPs [experimental group (exp), control group (con)].

For the CRT, the TIME x GROUP showed a significant difference with large effect size [$F_{(1,40)} = 3.602$, $p = 0.032$, $\eta_p{}^2 = 0.085$]. The *post-hoc* Bonferroni analysis showed an improvement only in the experimental group during the intervention [PRE vs. POST5: $M = 46.77$, $SD = 14.46$, t(19) = 3.23, $p = 0.027$; PRE vs. POST10: $M = 59.93$, $SD = 14.47$, t(19) = 4.14, $p = 0.001$] (**Figure 3**).

For the InT, the TIME x GROUP showed a significant difference with a large effect size [$F_{(1,40)} = 5.664$, $p = 0.005$, $\eta_p{}^2 = 0.124$]. Furthermore, the *post-hoc* Bonferroni analysis showed an improvement only in the experimental group during the intervention and only at the end of the 10-week training program [PRE vs. POST10: $M = 73.61$, $SD = 23.028$, t(19) = 3.19, $p = 0.030$] (**Figure 4**).

There were differences in adherence to the sessions between the two periods (supervised vs. online). There was 94% adherence during the supervised period and 71% adherence during the lockdown. An RM ANOVA was done to compare the evolution of the five sessions developed under supervision and online (RM ANOVA 5 × 2, a repeated measure for sessions, and between-subject factor for supervised vs. online training). When we compared the attendance of the participants to the sessions, there was a significant reduction in adherence to the online program [$F_{(1,58)} = 3.179$; $p = 0.014$; $\eta_p{}^2 = 0.052$]. The Bonferroni *post-hoc* analysis showed a significant reduction in attendance to session 3 [$M = 0.53$, $SD = 0.16$, t(29) = 3.31, $p = 0.049$], 4 [$M = 0.53$, $SD = 0.16$, t(29) = 3.31, $p = 0.049$] and 5 [$M = 0.83$, $SD = 0.16$, t(29) = 5.17, $p < 0.001$] compared to the first online session (**Figure 5**).

Finally, the effects of training on wellbeing were analyzed, taking into account three variables (positive affect, negative affect, and subjective vitality). The analysis was done for the three temporal moments (PRE, POST 5, POST 10) and the two groups (experimental vs. control group). The repeated-measures ANOVA revealed the absence of significant differences

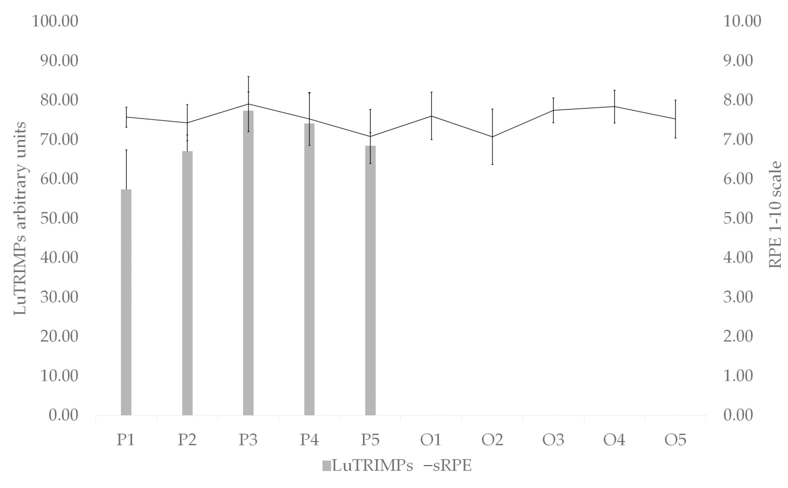

FIGURE 2 | Weekly (1–5) load in presential sessions (P) and online sessions (O) during quarantine periods expressed in RPE and LuTrimp. $n = 21$.

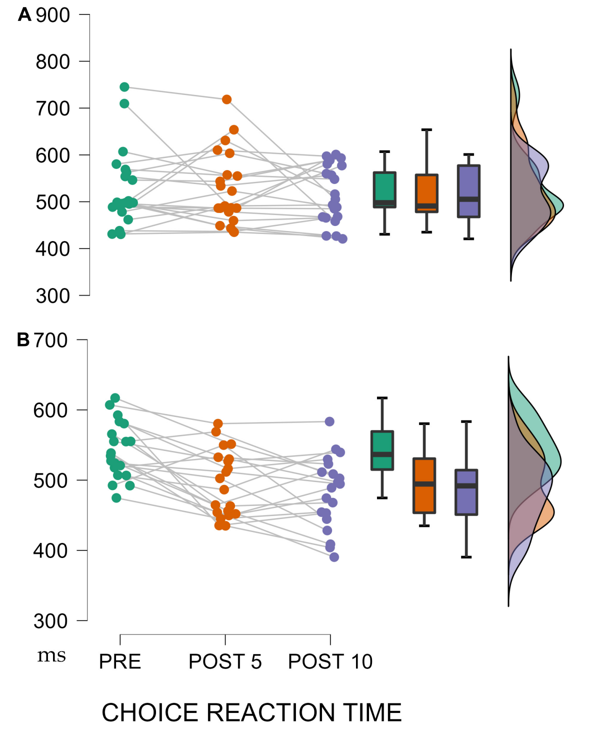

FIGURE 3 | (A) Control Group. **(B)** Experimental Group. Evolution of CRT during the training process. At the beginning of the study (PRE), after 5 weeks of supervised training (POST 5) and after another 5 weeks of online training during quarantine (POST 10). Significant results shown with *p*-values are for the experimental group. Data are shown as mean ± standard error.

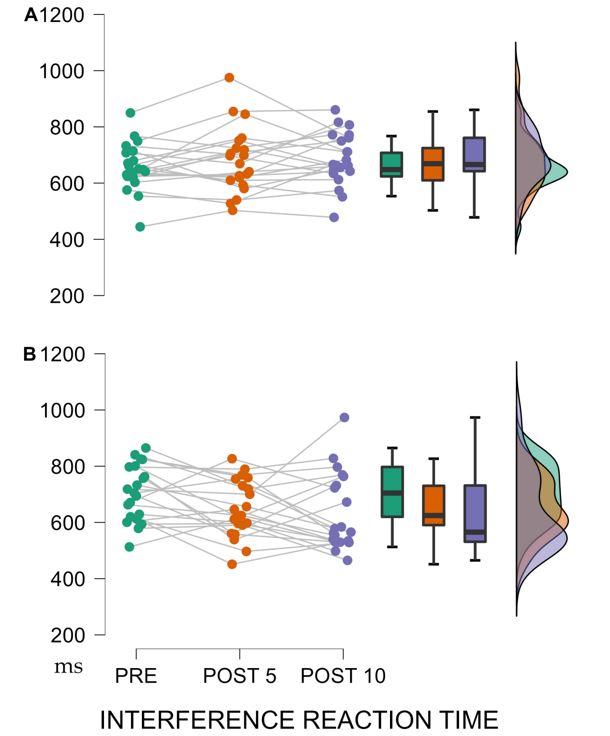

FIGURE 4 | (A) Control Group. **(B)** Experimental Group. Evolution of InT during the training process. At the beginning of the study (PRE), after 5 weeks of supervised training (POST 5) and after another 5 weeks of online training during quarantine (POST 10). Significant results shown with *p*-values are for the experimental group. Data are shown as mean ± standard error.

for the three variables, positive affect [$F_{(1,\ 40)} = 2.34$, $p = 0.11$, $\eta_p{}^2 = 0.11$], negative affect [$F_{(1,\ 40)} = 0.21$, $p = 0.979$, $\eta_p{}^2 = 0.001$], and subjective vitality, [$F_{(1,\ 40)} = 0.88$, $p = 0.42$, $\eta_p{}^2 = 0.04$]. Therefore, the results show that neither the supervised nor the online training phase affected wellbeing. Moreover, we saw a strong correlation between the three variables in the population (**Table 2**).

All the analyses were repeated considering the participant's sex, and no differences were found in any variable in the TIME × GROUP × SEX analysis [CRT $F_{(3,37)} = 0.431$, $p = 0.65$, $\eta_p{}^2 = 0.01$; InT $F_{(3,37)} = 0.274$, $p = 0.76$, $\eta_p{}^2 = 0.007$; Positive Affect $F_{(3,37)} = 1.54$, $p = 0.22$, $\eta_p{}^2 = 0.04$; Negative Affect $F_{(3,37)} = 1.58$, $p = 0.21$, $\eta_p{}^2 = 0.04$; Vitality $F_{(3,37)} = 0.783$, $p = 0.46$, $\eta_p{}^2 = 0.02$].

DISCUSSION

The objective of this study was to determine whether HIFT could improve cognitive functioning, measured as complex RT, and wellbeing, measured as vitality and positive and negative affects, in young college students. Although the participants declared a sedentary lifestyle during the previous 6 months of the study, their VO_2 max were within the normative values provided in the literature (Dwyer et al., 2005). As a result of the COVID-19 lockdown, a second objective, to analyze these variables and adherence during a quarantine period with online training, was included.

Regarding the participants' processing speed, we observed that 5 weeks of HIFT supervised training improved their RT (CRT and InT). Our findings are in accordance with the literature, providing moderate to strong evidence that exercise being performed at moderate to vigorous exercise intensity can improve processing speed (Erickson et al., 2019).

The different neurophysiological mechanisms that underlie such functional changes might explain the benefits of chronic PE for processing speed. For example, angiogenesis and neurogenesis are structural brain changes mediated by exercise (van Praag et al., 2005). BDNF has been shown to be an essential neurotrophin in this process (Notaras and van den Buuse, 2019). In this sense, a previous study observed that a 3-month HIFT program significantly increased resting BDNF levels in young adults (Murawska-Cialowicz et al., 2015). The chronic changes in the brain must be differentiated from the acute effects. It seems that the benefits of exercise on complex RT may, as an acute response, be mediated by transient phenomena such as the release of catecholamines at the central level (Meeusen and De Meirleir, 1995), which modulate information processing (Robbins and Everitt, 1995).

However, we still do not entirely understand the mechanism related to cognitive improvement (Stillman et al., 2020). In this

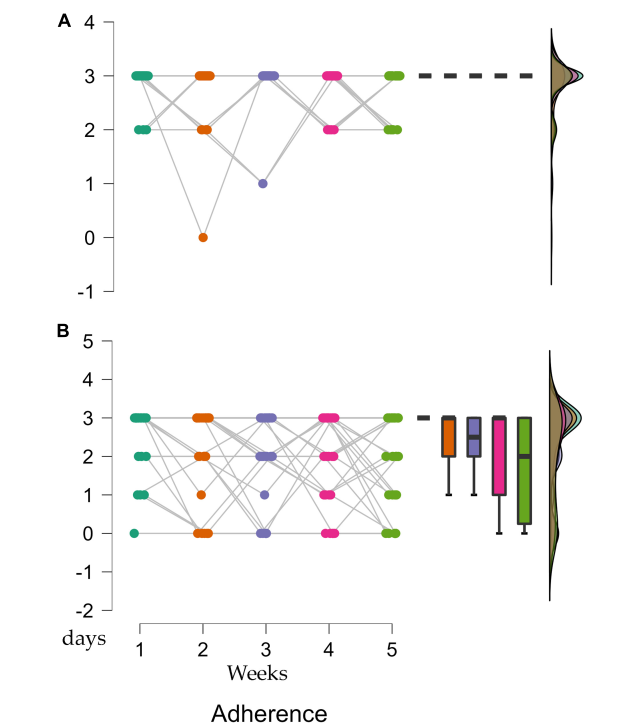

FIGURE 5 | (A) Adherence during the supervised period. **(B)** Adherence during the online period. Weekly adherence in the supervised (weeks 1–5) and online (weeks 6–10) periods. Differences were only present during the online training period.

TABLE 2 | Correlations between wellbeing variables.

	Variable	Positive affect	Negative affect	Vitality
Pearson's correlations in PRE				
Negative affect	*n*	42	–	
	Pearson's r	−0.578***	–	
	p-value	<0.001	–	
Vitality	*n*	42	42	–
	Pearson's r	0.665***	−0.463**	–
	p-value	<0.001	0.002	–
Pearson's correlations at POST 5				
Negative affect	*n*	41	–	
	Pearson's r	−0.531***	–	
	p-value	<0.001	–	
Vitality	*n*	41	41	–
	Pearson's r	0.797***	−0.551***	–
	p-value	<0.001	<0.001	–
Pearson's correlations at POST 10				
Negative affect	*n*	42	–	
	Pearson's r	−0.367*	–	
	p-value	0.017	–	
Vitality	*n*	42	42	–
	Pearson's r	0.712***	−0.349*	–
	p-value	<0.001	0.024	–

$^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$.

way, Stillman et al. (2016) proposed a multilevel system to study the underlying changes in cognitive functioning. Thus, cognitive changes can be produced by (a) molecular and cellular modifications (level 1), (b) structural and functional brain changes (level 2), and (c) behavioral and socioemotional changes (level 3). However, traditionally, the literature has focused on the first two levels, and there is a lack of evidence to understand the relations between behavioral and socioemotional changes with cognitive functioning (Stillman et al., 2016). Therefore, our study aimed to analyze the relationship between cognitive functioning and wellbeing, focusing on level 3 changes. Our hypothesis considered that hedonic and eudemonic variables of wellbeing would improve together with the RT variables.

However, the study results show that neither a 5-week HIFT supervised training program nor the online training during the COVID-19 quarantine affected this variable. Regarding the effect of training on these variables, the data contradict previous reports in the literature where acute, chronic PE and PT have been considered an effective tool to improve the wellbeing of young students (Cervelló et al., 2014; Garcia et al., 2015; Eather et al., 2019). However, some studies have found that high-intensity training did not cause significant changes in the wellbeing of this same population (Costigan et al., 2016). Moreover, data suggests an attenuated impact of the COVID-19 quarantine on the wellbeing variables in young students who presumably would not be burdened with responsibilities to the same degree as the adult population and thus experience less emotional distress (Brooks et al., 2020).

It has been shown that changes in cognitive functioning could be influenced by aspects of supervised training linked to mood and social relationships [could be related to level 3, as was proposed by Stillman et al. (2016)], such as (a) creating a structured and collaborative environment that favors positive reinforcement by peers and coaches; (b) a positive perception of social support; (c) achievement of goals; and (d) positive group dynamics (Lieberman et al., 2014). In agreement with these studies, our cognitive functioning improvements were higher during the supervised training than during the online training. However, improvements in processing speed were sustained through online training during the lockdown, unaffected by the reduction in adherence and social interactions. PE was probably sufficient to maintain unaltered mood and wellbeing, and the changes in processing speed could have been mediated by level 1 and 2 mechanisms (Stillman et al., 2016).

Although wellbeing was not modified due to the lockdown, significant differences in adherence were observed between the supervised and online phases. Self-determination theory (SDT) can explain the decrease in adherence (Deci and Ryan, 1985, 2000). SDT describes three psychological needs (autonomy, competence, and relatedness) that must be satisfied to increase the intrinsic motivation for a given activity. In our online training program, some of these needs were not satisfied, such as relatedness (Deci and Ryan, 1985) with peers and coaches, which has a significant impact on adherence to exercise (Kang et al., 2019), or the supervision of qualified professionals (Garber et al., 2011). In addition, recent studies have shown that people who reduced their PA during lockdown experienced decreased wellbeing (Brand et al., 2020; Faulkner et al., 2021). However, in our results, despite the correlation between positive and negative affect with vitality, the latter was not reduced in parallel with a decrease in adherence. Moreover, CRF is related to vitality in young people (Eddolls et al., 2018), and CRF can be maintained with a lower volume of exercise if the intensity of the activity is conserved (Spiering et al., 2021). Given that there were no changes in the exercise intensity throughout the training program, the reduction in adherence in this study probably did not affect CRF, and hence, vitality was not altered.

Our study demonstrates that HIFT can improve cognitive functioning in young university students and could be successfully applied through online training under lockdown circumstances, maintaining the exercise intensity and improving cognitive functioning. Moreover, as we have demonstrated, it is possible to maintain the subjective exercise intensity (measured by RPE) of the HIFT training in the online approach, with no adverse changes in wellbeing. However, if we want to use this methodology in future lockdowns, it would be interesting to analyze the lockdown training protocols from the SDT perspective, trying to overcome psychological needs deficiencies during the quarantine periods.

Finally, our study did not find any sex differences in the analyses performed. A previous meta-analysis showed discrepancies in sex differences. For example, Barha et al. (2017) found that sex was a strong moderator in the exercise-cognition relationship in their meta-analysis, with more pronounced improvements for women. However, Falck et al. (2019) did not find this relationship in their meta-analysis. In any case, both meta-analyses were done in older people. Some old studies showed that older women participated in lower leisure-time PA than older men (Lee, 2005), or reported lower frequencies of physical activities (Kaplan et al., 2001). In addition, sedentarism has a worse cognitive impact in women than in men (Fagot et al., 2019). Thus, Barha and Liu-Ambrose (2018) proposed that the increase in daily PA could be greater for older women than for older men, and this difference could promote more significant cognitive improvements in women. However, recent studies have shown that, nowadays, older women are less sedentary and do more PA than men (Wennman et al., 2019; Lopez-Valenciano et al., 2020). Suppose PA determines the cognitive functioning improvements after a PT period. In that case, present and future research will find a sex gap with better improvements in older men.

Regarding this study, we do not know any review of sex differences in young university students on the exercise-cognition relationship. Thus, according to the results of our study, sex does not moderate the improvement in processing speed after chronic exercise in young people.

This study investigated whether, in young adults, supervised and unsupervised HIFT can influence wellbeing and cognitive functioning, as empirical evidence regarding the effect of PEs on wellbeing and cognitive functioning is scant in this age group (Stillman et al., 2020). However, we did not find evidence that exercise-related changes in socioemotional parameters are associated with alteration of cognitive functioning, as previously proposed (Stillman et al., 2016). We described our training methodology with HR records and used ventilatory thresholds to control the exercise load. The implications that arise from the findings of our study broaden our knowledge on the influence of HIFT on cognitive functioning and wellbeing in younger adults.

LIMITATIONS

As a result of lockdown, the main limitation to this study was that it was impossible to carry out post-training fitness tests, so we do not know if the observed changes in cognitive functioning are related to improvements in fitness. Therefore, it would be interesting for future research to look into the implicit mechanisms related to physical fitness that could potentially explain improvements in complex RT. Moreover, the study did not employ allocation concealment, which indicates a possible source of bias.

CONCLUSION

On the one hand, HIFT training improves processing speed, measured through two complex RT tasks (CRT and InT) in young college students, without mediation by changes in psychological wellbeing. Also, it was observed that a training program during a quarantine period, forced by the global COVID-19 pandemic, promoted the maintenance of RT improvements previously achieved during a supervised training program. On the other hand, it was observed that this situation did not have adverse effects on this population's wellbeing. However, it negatively affected adherence to the online training program, possibly because of the suppression of typical factors linked to training supervision and interactions with peers and coaches.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Miguel Hernández University Ethics Committee (UMH.CID.DPC.02.17). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JB-F, LC-H, DP, and EC contributed to the conception and design of the study. JB-F organized the database. JB-F, LC-H, and DP performed the statistical analysis and wrote the final manuscript. JB-F and LC-H wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

This work was supported by Grant RTI2018-098335-B-I00 funded by MCIN/AEI/10.13039/501100011033/ "ERDF A way of making Europe."

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BRIEF RESEARCH REPORT
published: 03 June 2022
doi: 10.3389/fnbeh.2022.901491

Effects of Outdoor Walking on Positive and Negative Affect: Nature Contact Makes a Big Difference

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It has been consistently demonstrated that physical exercise is a cost-effective way to promote emotional well-being. However, the environment in which it takes place might amplify or mitigate this beneficial effect. The present study aimed at comparing the effects of walking in a natural or urban field setting on positive and negative affect. For this purpose, 150 students (46 female, 104 male; mean age: 20.2 years) were randomized into one of three groups: Green Walking (GW, n = 50), Urban Walking (UW, n = 50), or no-exercise (control; CTRL, n = 50). Positive and negative affect ratings were collected for each participant before and after walking (or before and after attending a class in the CTRL group). Exercise parameters (duration, intensity, weather conditions, group size) were identical in the GW and UW groups. The walking routes differed in terms of vegetation density, proximity of water, presence of traffic, and amount of asphalted surfaces. Participants in the GW and UW groups reported significant reductions in negative affect pre- to post walking. However, positive affect was increased only for participants in the GW group. This finding may have meaningful implications for mental health professionals who treat patients with significant emotional distress or mood instability. Several explanations are discussed as potential mechanisms for the more beneficial effect of Green walking, and presented as an important avenue for future research.

Keywords: green exercise, nature, positive affect, walking, nature relatedness, pollution

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Specialty section:
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

Received: *22 March 2022*
Accepted: *12 May 2022*
Published: *03 June 2022*

Citation:
Legrand FD, Jeandet P, Beaumont F and Polidori G (2022) Effects of Outdoor Walking on Positive and Negative Affect: Nature Contact Makes a Big Difference. Front. Behav. Neurosci. 16:901491. doi: 10.3389/fnbeh.2022.901491

INTRODUCTION

Emotions have traditionally been categorized on the basis of two broad dimensions, namely pleasantness, and arousal. Watson and Tellegen (1985) have suggested a 45-degree rotation of these axes to yield dimensions of positive and negative affect. While negative affect has been widely associated with the development of emotional disorders such as anxiety and mood disorders (Brown and Barlow, 2009), the role of positive affect in connection to these conditions remains relatively unexplored (Garland et al., 2010). In general, positive affect refers to pleasant emotional states, including joy, enthusiasm, energy, amusement, and alertness to cite a few. Of note, positive affect is not simply the opposite of negative affect, but rather an independent construct not always inversely correlated with negative affect (Gloria and Steinhardt, 2016), although this has historically been debated in the literature with other authors considering them to be bipolar ends of the same dimension (Ong et al., 2010).

Positive affect has been associated with many health-related benefits in clinical and non-clinical populations. For instance, research suggests it may increase stress resilience, as well as overall mental health and well-being (Lyubomirsky et al., 2005; Garland et al., 2010). In addition, positive affect has been associated with an improved functioning of the immune system (Diener and Seligman, 2002), which is of particular relevance in the current pandemic context. Likewise, preliminary research has established that explicitly targeting positive affect in mood and anxiety disorders treatment through therapeutic strategies or modules, such as well-being therapy (Barlow et al., 2017), positive psychotherapy (Hope et al., 2006), or an increase in the regulation of positive emotion (Eckeland et al., 2021) can lead to clinically significant improvements in symptoms.

Taken together, the scientific literature then clearly suggests that there is a benefit to increasing positive affect, but surprisingly, most of the psychotherapy interventions continue to focus on targeting negative affect. Accordingly, most studies of leading treatments for emotional disorders remain focused on evaluating outcomes of reduced symptoms of negative affectivity (Garland et al., 2010) rather than addressing positive affectivity. The question remains if and how existing interventions can modify positive affect even though it is not their central focus.

There is an extant literature suggesting that physical exercise might be well-suited for enhancing positive affect (Reed and Ones, 2006; Ekkekakis et al., 2011; Chan et al., 2019). Mood benefits (increased positive affect and/or decreased negative affect) have been consistently reported after a single bout of aerobic or anaerobic exercise at low or moderate intensities, and durations up to 35 min. However, individual responses to exercise can be moderated (either enhanced or lessened) by subtle factors of the physical or social environment, such as temperature, humidity, presence of mirrors, odors, etc. A relatively recent area of investigation has suggested that green exercise (that is, engaging in physical activity in the presence of Nature) could enhance the mood-boosting effect of exercise. According to Ulrich et al. (1991), this effect is linked to the fact that natural environments invoke feelings of interest and calm, thereby promoting positive affect. Another explanation recently offered by Baxter and Pelletier (2019) posits that human beings have a basic psychological need for nature relatedness. In congruence with the assumptions made by the Self-Determination Theory (SDT; Ryan and Deci, 2017), meeting this need would lead to vitality and well-being, as is the case with the other basic psychological needs (e.g., relatedness or competence). Several published studies have provided support for a positive relationship between natural environments and psychological well-being. For example, a large observational study including almost 95,000 adult participants revealed that residential greenness was associated with lower prevalence rates of major depressive disorder (Sarkar et al., 2018). Similarly, an experience-sampling study which examined the relationship between natural features of the environment and psychological well-being found that exposure to natural features (e.g., trees, birdsong) had an immediate beneficial effect on well-being lasting several hours (Bakolis et al., 2018). Hence, it is not surprising that many researchers are assuming that nature-based exercise environments promote greater improvements in psychological well-being than exercise in other environment types. In their systematic review, Thompson-Coon et al. (2011) confirmed the more beneficial effects of outdoor exercise on feelings of anger, confusion, tension, depression, enjoyment, energy, and revitalization. However, studies presented in this review have done little more than comparing indoor exercise with physical activity in any outdoor environment, which for the most part consisted of urban spaces. Only two studies have directly compared the psychological responses to exercise in a green vs. urban environment to date. In the study by Hartig et al. (2003), walking in oak-sycamore woodland nature settings increased positive affect and reduced anger whereas urban walks in a city retail and office space had the opposite effect. The second one is the study by Park et al. (2011) showing that tension, anxiety, fatigue, and confusion were decreased by a nature walk, but not by an urban walk of equivalent duration. Unfortunately, an important limitation of these two studies is that exercise intensity was not measured. The lack of experimental control for participants' level of exertion is a significant issue given the well-established influence of this exercise parameter on affective responses to exercise (Ekkekakis et al., 2011). More specifically, an inverse relationship has been reported between exercise intensity and psychological well-being in the literature review by Ekkekakis et al. (2011), with positive affective changes occurring during and following exercise of both light and moderate intensities, but not for high or very high-intensity exercise.

Thus, the purpose of the present study was to more rigorously evaluate the hypothesis that Nature exposure has the possibility to enhance the affective benefits of outdoor physical activity. In this aim, we conducted a large randomized controlled trial comparing emotional changes following a 30-min outdoor exercise bout performed at a controlled and standardized level of intensity in either a natural countryside setting or an urban surrounding.

METHODS

Study Design and Participants

We employed a randomized controlled design with three different groups: green walking (outdoor walking in connection to Nature), urban walking (outdoor walking in an urbanized area), or control (regular class time without any physical activity). Randomization was computer-generated through permuted blocks in a 1:1:1 ratio. Given the typical effect sizes (*ESs*) for exercise-induced affective changes (0.4–0.5, Reed and Ones, 2006), the *a priori* power analysis for the within-between interaction of an ANOVA with three independent groups and two measurement periods (pre and post) with the settings of $f = 0.20$, $\alpha = 0.05$ (p-value), $1 - \beta = 0.95$ (power) yielded a needed total sample size of 102 participants (G*POWER, Faul et al., 2007). A total of 150 undergraduate students from the Sport and Physical Education Department at a university in northeastern France were recruited. The mean age of this sample was 20.2 years ($SD = 1.3$) and 69.3% were male. The data were collected as part of a 2-h practical class, but at the time of data collection, the students were not aware of the exact hypotheses of the study. In particular, those belonging to the green and urban walking groups believed they were receiving an identical physical exercise stimulus. However, since experimenters knew which participants were in which group, our experiment can only be said to be a single-blinded study. Students' academic timetables were carefully scrutinized to ensure that they did not exercise prior to our experiment. At the beginning of their visit, participants completed an informed consent and reported basic demographic information (age, sex).

Instruments

Positive affect (PA) and negative affect (NA) were assessed using the Positive And Negative Affect Schedule (PANAS; Watson et al., 1988). This consists of 20 adjectives, each of which is rated on a 5-point scale from 1 (very slightly or not at all) to 5 (extremely). Ten items contribute to the positive affect scale (e.g., enthusiastic, excited, alert) and 10 to the negative affect scale (e.g., upset, afraid, irritable). Participants were asked to think about « how they were feeling right now» when completing the scales. Ratings were summed to generate positive and negative affect scores, each varying from 10 to 50.

Procedure

Participants in the green walking group (GW, n = 50) were asked to walk briskly for 30 min as if they were late for class. The walking sessions all occurred at the beginning of the afternoon (between 2:00 p.m. and 4:00 p.m.), were conducted outdoors, on a walkway alongside a canal, and were led by the first author. This walkway was lined with trees/bushes and passed through a mix of wine-growing areas, parklands, as well as wide open greenfields. Sessions were conducted in subgroups of 12–13 participants, which required the exercise bout to be repeated on four separate days to get through the whole group. Weather was quite similar during the testing days and quite normal for the season in Northeastern France; that is around 7°C–9°C, with no precipitation, and moderately cloudy conditions. The physical exercise stimulation was administered with the same parameters (type, duration, intensity, mode of delivery, subgroups size, time of day, and weather conditions) for participants in the urban walking group (UW, n = 50). However, walking sessions were conducted in a metropolitan urbanized district consisting of residential developments, commercial and nonresidential buildings, light industry, car parks, and totally asphalted streets. **Figure 1** shows satellite images of the two

FIGURE 1 | Satellite images of exposure environments (Urban, Green).

exposure environments (green and urban) used in the present study.

On the contrary, the control group consisted of students from the same department at the same university who did not walk but attended a regular class lecture (CTRL, $n = 50$). This group involved two classes of 25 students randomly selected from a total of nine classes of the same year group at this department. For these two classes, the lecture took place at the same time of day as the walking sessions planned for participants in the UW and GW groups (between 2:00 p.m. and 4:00 p.m.). The lecture lasted 60 min and was divided into two 30-min modules; the first one was on the mental health benefits of outdoor physical activity, and the second one expanded on ideas presented right before toward the development of low-cost and effective nature-based interventions. Participants in both groups took the PANAS before and after walking (or before and after the first 30-min lecture module for those in the CTRL group). Heart rate was assessed *via* self-palpation of the radial pulse on the nondominant hand at the end of the walking sessions in the GW and UW groups.

Data Analysis

A mixed design with two independent variables was used: (a) one between-participant variable (GW, UW, and CTRL groups), and (b) one within-participant variable (pre- and post-intervention assessments). There were two dependent variables: (a) Positive Affect (PA), and (b) Negative Affect (NA). Therefore, two 3 (Groups) × 2 (Time Points) mixed-design ANOVAs were conducted. The significance level was $\alpha = 0.05$. Since we used multiple comparisons in *post-hoc* tests, the level of significance was partly modified by a Bonferroni correction to minimize the familywise error rate and maintain statistical power (Vincent, 2005). Effect sizes, Cohen's $d = (Mi–Mj)/SD_{pooled}$, were computed to compare the magnitude of PA and NA changes between participants who walked in connection to Nature and those who walked in the urbanized district. One-way ANOVAs and Chi-2 tests were also performed to assess whether there were baseline differences between groups. Finally, an independent sample Student' *t*-test was used to compare the mean heart rate recorded at the end of the walking session for participants in both the GW and UW groups.

RESULTS

Preliminary Analyses

All participants provided data pre- and post-intervention (see **Figure 2**). There were no differences between groups neither in terms of gender distribution $\chi^2_{(2)} = 3.16$, $p = 0.207$, nor in terms of age, $F_{(2,147)} = 1.69$, $p = 0.188$. Likewise, PA and NA scores did not significantly differ between groups at baseline ; $F_{(2,147)} = 2.69$, $p = 0.072$ and $F_{(2,147)} = 2.91$, $p = 0.064$ respectively. Lastly, heart rate at the end of the walking session in the GW group [$M = 112.6$ bpm ; that is 58.3% of age-predicted maximal heart rate (MHR)] was found to be statistically identical to that reported in the UW group ($M = 111.2$ bpm; i.e., 57.6% of age-predicted MHR), $t_{(98)} = -0.38$, $p = 0.706$. These values reflect physical exercise performed at «moderate» (55%–69% of age-predicted MHR) intensity according to the American College of Sports Medicine (Pollock et al., 1998).

Positive Affect and Negative Affect

Descriptive statistics for the pretest and posttest PA and NA scores are given in **Table 1**. As can be seen, the mixed ANOVAs revealed significant Time × Group interaction for both variables. With regard to Positive Affect (PA), *post-hoc* analyses indicated that the mean PA score significantly increased from pre- to posttest for participants in the GW group ($t_{(49)} = 3.93$, $p = 0.002$) whereas it significantly decreased for participants who did not walk (CTRL group, $t_{(49)} = -3.50$, $p = 0.009$). Importantly, PA was not found to change significantly from pre- to post-walking among participants who exercised in the urban setting, $t_{(49)} = 2.03$, $p = 0.661$. The effect size comparing PA change in the two walking groups (i.e., GW *vs*. UW) was large, Cohen's $d = 0.83$.

Results for Negative Affect were quite different. More specifically, follow-up pairwise comparisons demonstrated that, regardless of the environment conditions, walking for 30 min at moderate intensity significantly reduced NA (GW: $t_{(49)} = -6.54$, $p < 0.001$; UW: $t_{(49)} = -5.91$, $p < 0.001$). On the other hand, NA remained statistically unchanged for participants in the control group, $t_{(49)} = -1.83$, $p = 0.995$. The effect size comparing NA change in the two walking groups was negligible, Cohen's $d = -0.11$.

DISCUSSION

This study sought to directly compare the emotional effects of 30 min of outdoor walking in a green vs. urbanized setting. We found that green exercise significantly improved Positive Affect and significantly reduced Negative Affect, whereas the same exercise stimulus in a metropolitan urbanized area only decreased Negative Affect.

The finding that Positive Affect increased in the green but not in the urban walking group supports our research hypothesis and is in line with the findings from Hartig et al. (2003) or Park et al. (2011). However, several differences limit the comparability of results: (a) Hartig et al. (2003) asked half of their participants to perform various cognitive tasks before walking (attentional and memory tests); (b) exercise intensity was neither measured nor controlled in these two previous studies; (c) positive affect was measured using a relatively crude and nonspecific instrument in Hartig et al.'s (2003) study (the Zuckerman's Inventory of Personal Reactions; ZIPERS, Zuckerman, 1977); and (d) there was no sedentary control group in Hartig et al.'s (2003) study.

Several mechanisms may be proposed to account for enhanced affective benefits during and following green exercise. First, air quality is one of the mechanisms outlined in Hartig et al.'s (2014) model of the links between Nature environments and well-being. As discussed by Zhang et al. (2017), both short and long-term exposures to polluted urban air, and particularly to fine particulate matter of aerodynamic diameter ≤2.5 μm ($PM_{2.5}$), reduce subjective well-being and increase the rate of depressive symptoms. There is growing evidence from both toxicological and clinical studies that short-duration exposure

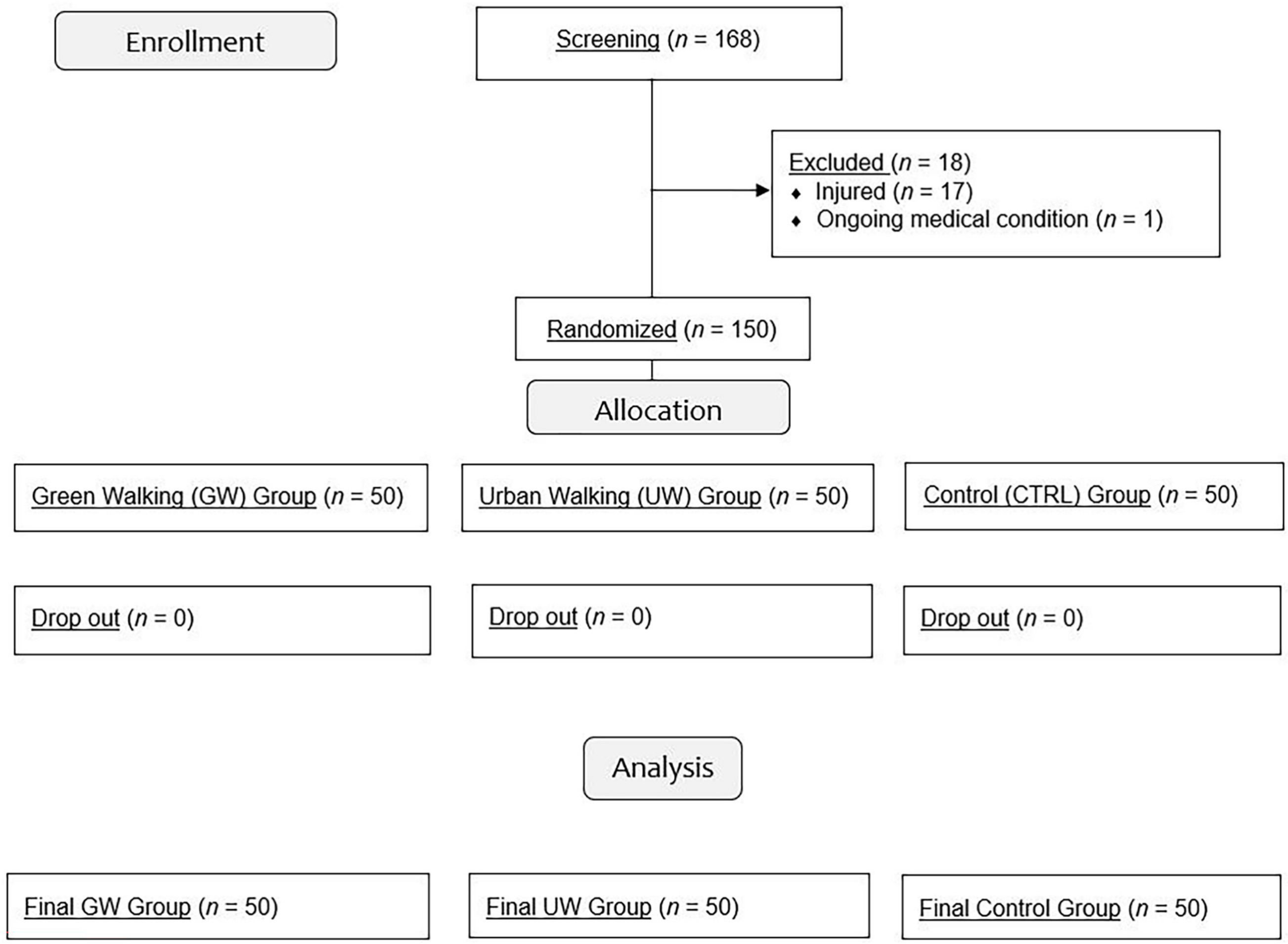

FIGURE 2 | Flowchart of study participants through the trial.

TABLE 1 | Descriptive statistics for positive and negative affect scores as a function of Group and Time, ANOVA results, and effect sizes of the differences between the two intervention groups (Green Exercise vs. Urban Exercise) on the change score.

	Pretest		**Posttest**		$F_{(2,147)}$	**Cohen's *d* [95% CI]**
	M	***SD***	***M***	***SD***	**Time × Group**	
Positive Affect (PA)					15.54**	0.83 [0.42, 1.23]
GW group (*n* = 50)	29.90	5.84	32.58	6.18†		
UW group (*n* = 50)	31.60	6.82	30.22	7.16		
CTRL group (*n* = 50)	28.38	5.94	26.00	6.26†		
Negative Affect (NA)					6.56*	−0.11 [−0.57, 0.28]
GWgroup (*n* = 50)	16.50	5.28	12.56	2.60†		
UWgroup (*n* = 50)	17.18	6.50	13.62	3.65†		
CTRL group (*n* = 50)	14.70	3.81	13.60	3.25		

*GW, Green Walking; UW, Urban Walking; CTRL, control. *p ≤ 0.01; **p ≤ 0.001; †significant within-group score change from pretest to posttest (post-hoc Bonferroni-corrected tests).*

to combustion-derived particles leads to immediate detrimental affective changes (World Health Organization, 2013). Reviews of the research literature report that vegetation decreases levels of air pollution by enhancing the removal of air pollutants through adherence to plant surfaces (adsorption) and/or absorption by leaf stomata (Anderson and Gough, 2021). Connecting with Nature *via* physical activity can serve as an alternative to polluted urban air. A second explanation might be that Nature immersion undergone during the green walking session contributed to the satisfaction of the need for nature relatedness which, according to Baxter and Pelletier (2019), should be viewed as an additional basic human psychological need. A fundamental tenet of the Self Determination Theory (SDT; Ryan and Deci, 2017) is that a direct relationship exists between basic psychological needs satisfaction and psychological well-being. Studies undertaken in various sports and physical activities (e.g., Gagné et al., 2003 in a sample of gymnasts; Quested and Duda, 2010 in a sample of dancers) tend to support SDT hypotheses regarding the satisfaction of basic needs as a predictor of performers' well-being (i.e., self-esteem, positive affect). Finally, one of the classic explanations arising from environmental psychology, Attention Restoration Theory (ART; Kaplan, 1995), suggests that one's affective state is linked to attentional resources, and defines two types of attention: directed and involuntary attention. Directed attention involves mental effort and concentration and, if overused, leads to mental fatigue and worsened affective state. Natural environments have been shown to promote the use of involuntary attention, providing an opportunity for recovery from mental fatigue, which is associated with positive change in affect (e.g., Faber-Taylor and Kuo, 2009).

By showing that green exercise has especially positive effects on emotional well-being that go beyond the benefits of being physically active, the present study identifies the various opportunities that outdoor sports can offer in order to help prevent or alleviate mental health problems. Some research teams have provided preliminary data suggesting that physical activity in a natural environment might produce greater mental health benefits than physical activity elsewhere (e.g., Mitchell, 2013). The large cross-sectional health survey by Mitchell (2013) revealed that the odds of poor mental health among those regularly using woods or forests for physical activity were almost 50% lower (OR = 0.56) compared to non-users. However, considerably more research is needed to establish the therapeutic benefits of green exercise in the treatment of mental disorders for which low positive affect is a prevalent feature (i.e., depressive disorders).

Our findings come with some limitations. First, future research should aim at increasing the generalisation of green exercise practice, using a wider variety of social groups while exercising, and involving various degrees of «naturalness». Future research should also consider assessing the impact of green exercise on a wider range of psychological outcomes (stress, anger-hostility) and with different population samples (non-regular exercisers, indoor exercisers, highly depressed individuals, and individuals raised in non-urban areas). The sample in the current study consisted of young people who were engaging regularly in physical activities (including activities in the wilderness such as mountain-biking and kayaking) due to their curriculum, and were thus likely to be relatively healthy and positively oriented towards Nature. Finally, the present study focused on acute exercise effects, but it may be advantageous to study the effects of longer-term green exercise programs, particularly if exercise is aimed at individuals with depressive symptoms. Indeed, available recommendations regarding optimal exercise «dosages» based on research including individuals with clinical depression state that exercise interventions should last at least 10 weeks (Rethorst and Trivedi, 2013).

CONCLUSION

In conclusion, despite the above-mentioned limitations, our findings have implications for public mental health and deserve the emerging discussion surrounding ecosystem services (Hughes et al., 2013). In addition, greater awareness of the indirect benefits to humans of natural environments could help contribute to their protection and maintenance.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Comité d'Ethique de Recherche en Sciences et Techniques des Activités Physiques et Sportives (CER STAPS). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

FL and PJ contributed to the conception and design of the study and drafted the manuscript. FL and GP acquired the data and performed the data analysis. FL, FB, and PJ edited and revised the manuscript. All authors interpreted the results, read, and approved the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers | Frontiers in Behavioral Neuroscience

TYPE Original Research
PUBLISHED 28 July 2022
DOI 10.3389/fnbeh.2022.944193

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OPEN ACCESS

EDITED BY
Suk Yu Sonata Yau,
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SPECIALTY SECTION
This article was submitted to
Emotion Regulation and Processing,
a section of the journal
Frontiers in Behavioral Neuroscience

RECEIVED 14 May 2022
ACCEPTED 04 July 2022
PUBLISHED 28 July 2022

CITATION
Almarcha M, González I, Balagué N and Javierre C (2022) Prescribing or co-designing exercise in healthy adults? Effects on mental health and interoceptive awareness. *Front. Behav. Neurosci.* 16:944193. doi: 10.3389/fnbeh.2022.944193

Prescribing or co-designing exercise in healthy adults? Effects on mental health and interoceptive awareness

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Universal exercise recommendations for adults neglect individual preferences, changing constraints, and their potential impact on associated health benefits. A recent proposal suggests replacing the standardized World Health Organisation (WHO) exercise recommendations for healthy adults by co-designed interventions where individuals participate actively in the decisions about the selected physical activities and the effort regulation. This study contrasts the effects on mental health and interoceptive awareness of a co-designed and co-adapted exercise intervention with an exercise program based on the WHO recommendations for healthy adults. Twenty healthy adults (10 men and 10 women, 40–55 y.o.) participated voluntarily in the research. They were randomly assigned to a co-designed exercise intervention (CoD group) and a prescribed exercise program (WHO group). Supervised online by specialized personal trainers, both programs lasted 9 weeks and were equivalent in volume and intensity. The effects of the exercise intervention were tested through personal interviews, questionnaires (DASS-21 and MAIA) and a cardiorespiratory exercise test. Intragroup differences (pre-post) were assessed using the Mann-Whitney Wilcoxon test and intergroup differences through Student's *t*-tests. Effect sizes were calculated through Cohen's d. Interviews were analyzed through thematic analysis. Eleven participants completed the intervention (CoD = 8, WHO = 5). Both groups improved, but non significantly, their cardiorespiratory testing results, and no differences were found between them post-intervention. Mental health was only enhanced in the CoD group ($p < 0.001$), and interoceptive awareness improved in seven of the eight scales in the CoD group ($p < 0.001$) and only in 3 scales in the WHO group ($p < 0.01$). In conclusion, the co-designed intervention was more effective for developing mental health, interoceptive awareness, autonomy, and exercise self-regulation than the WHO-based exercise program.

KEYWORDS

personalized exercise, mental health, affective wellbeing, complex systems approach, network physiology of exercise, WHO recommendations, exercise adherence, self-awareness

Introduction

Prescribing an adequate exercise program to promote health in the adult population has been a central research issue (Pollock et al., 2000). Two main types of programs (aerobic, resistance, and a combination of both) have been investigated due to their different physiological impact and proven benefits (Kenney et al., 2015). Based on the available research, the American College of Sports Medicine (ACSM) and the World Health Organization (WHO) have converged on the type of activity and minimum dose in their guidelines for exercise prescription in health and disease (Riebe et al., 2018) with light adaptations depending on the age and type of disease (Bull et al., 2020; Bushman, 2020). However, some authors have questioned the theoretical and methodological assumptions of this one-size-fits-all approach (Balagué et al., 2020a), and have proposed person-centered guidelines in line with current therapeutic tendencies (Carpinelli, 2009; Greenhalgh et al., 2014; Zimmer et al., 2018; Wackerhage and Schoenfeld, 2021).

The self-determination theory (SDT)-based exercise referral consultation (Jolly et al., 2009; Deci and Ryan, 2013) proposes interviewing participants before the exercise program about their perceptions of autonomy and motivational regulations. The aim is provide choices of activities, support initiations and relevant information for being physically active. Limiting their intervention to the beginning of the program, professionals do not guide adaptations during the program. However, a permanent interaction professionals-practitioners during this period may ensure adequate adjustments of exercise characteristics to keep participant's wellbeing and adherence, and develop their self-knowledge and autonomy.

It is known that meaningful and motivating practices increase exercise adherence and, thus, its health-related effects (Salmon, 2001; Williams, 2008; Carek et al., 2011; Stonerock et al., 2015). Additionally, performing new and challenging activities seem to satisfy basic psychological needs (Fernández-Espínola et al., 2020).

The effects of regular exercise on depression and anxiety, the two most disabling mental disorders in both sexes, and among the top 25 leading causes of the global health-related burden (GBD 2019 Diseases and Injuries Collaborators, 2020) are well known. Mental health and emotional wellbeing improve through regular exercise (Paluska and Schwenk, 2000; Ströhle, 2009; Stanton and Reaburn, 2014; Schuch et al., 2016), and is also associated with a reduced risk of suffering from emotional disorders (Bernstein and McNally, 2018).

From a complex systems perspective, health has been defined as a dynamic product of the interplay between the external environment and internal physiology (Sturmberg et al., 2019). The health state can change in response to somatic conditions, social connectedness, emotional feelings, and subjective perceptions (Sturmberg, 2019). Within this paradigm, the stability of a healthy state can be achieved in multiple ways, and nonlinear, i.e., non-proportional, individual training effects may occur after exposure to exercise and training loads (Hristovski and Balagué, 2010). Even the same exercise intensity, which may promote positive adaptations in a specific person or context, may produce overtraining or no effects in another person or particular context (Hristovski et al., 2010).

The ACSM and the WHO recommend performing a minimum of 150 min of aerobic exercise at a moderate intensity or 75 min of vigorous-intensity exercise in combination with resistance training at least two times per week, using two sets of 8–15 repetitions with 60% of one-repetition maximum (American College of Sports Medicine, 2017; World Health Organization [WHO], 2020). These universal recommendations assume the existence of decontextualized realities (Jones et al., 2017) and ideal or prototypic fitness and health states. Although fitness is often associated with strength and conditioning, the fittest is not the strongest or endured in biological evolution but the most diverse (Pol et al., 2020). Accordingly, fitness has been redefined as the ability to survive in a broad range of contexts to adapt to socio-psycho-biological challenges (Balagué et al., 2020b; Hristovski and Balagué, 2020).

Even though most studies present favorable results applying the recommended types of exercise, systematic reviews and meta-analyses on exercise prescription indicate the lack of high-quality studies showing the sustainability of standardized programs (Sørensen et al., 2006) and the need for personalizing the recommendations (Zimmer et al., 2018). In line with personalized exercise medicine, it has been advised to reorient the main aims of exercise prescription and redefine the roles of health care exercise professionals interacting with users/patients (Balagué et al., 2020b). Notably, it has been suggested to develop the autonomy and self-regulation of users/patients through their active involvement in the co-design of exercise proposals and workload adjustments (Almarcha et al., 2021).

Due to substantial inter-individual differences and personal contexts, the development of interoceptive awareness of users/patients seems crucial for achieving self-knowledge and self-responsibility to select and regulate exercise workloads adequately (Pol et al., 2020; Montull et al., 2022). Interoceptive awareness is the ability to identify, access, understand, and respond appropriately to the patterns of internal signals that allow to engage in life challenges and ongoing adjustments (Craig, 2015). Regulating daily active and resting periods, frequency, intensity, and duration of exercise promotes healthy mind-body states. Almarcha et al. (2021) sustain that education on self-regulation of psycho-emotional and physical states is essential to promote health and affective wellbeing during home-based teleworking. The authors propose to healthcare professionals: (a) redefine fitness states, (b) refocus the aims of home-based exercise, (c) guide users from dependency to autonomy, (d) promote co-adaptive and co-learning processes, and (e) develop interoceptive awareness. As far as we know, no studies have evaluated the interoceptive awareness effects of a co-designed exercise program in healthy adults.

The present study aimed to contrast the effects of a co-designed exercise intervention with a WHO-based program on mental health and interoceptive awareness in healthy adults. Specifically, it was hypothesized that a co-designed intervention reduced further depression, anxiety, and stress levels and increased further interoceptive awareness and self-regulation.

Materials and methods

Participants

Twenty healthy adults (10 men and 10 women) aged between 40 and 50 y.o., with a medium socioeconomic status, higher education level and non-involved in regular physical activity, volunteered to participate in this study. Considering a target power of 0.8, a significance level of $p < 0.05$, and a medium effect size (0.5), the total sample size calculated using the software G * Power v3.1.9.7 was 12 participants. To compensate for the possible loss of follow-up, the proposed sample was 20 participants.

The exclusion criteria were the following: (a) report any contraindications and injury that prevented from physical exercise; (b) prohibitions of physical testing interventions; and (c) pacemaker dependent, not in sinus rhythm, pregnant, had a BMI greater than 30 kg/m^2 or had known carotid or femoral artery stenosis.

After being informed about the study procedure and sign an informed consent, participants performed a cardiorespiratory exercise test and responded to two questionnaires (see below) through Google forms. All responses were coded to ensure data privacy and anonymity. After it, they were randomly divided into two groups of 10 members each that followed two different exercise programs during 9 weeks: (a) a co-designed exercise intervention (CoD group), and (b) a standardized exercise program based on WHO recommendations (WHO group). Both groups had similar fitness status and questionnaire scores. Participants were randomly assigned to 7 personal trainers (Sport Science graduates) with a minimum of 3 years of professional experience and specifically trained for 2 weeks to develop both intervention programs. Each coach trained virtually 2–3 participants. They supervised participants' online training and interacted with them twice a week. They also had meetings with the research coordinator to follow up on the intervention weekly. The research project was approved by the Comité d'Ètica d'Investigacions Clíniques de l'Administració Esportiva de Catalunya (ref. 07/2015/CEICEGC). A total of 7 participants (CoD = 2, WHO = 5) did not complete the intervention program.

Procedure

Co-designed exercise intervention

It had two main objectives: (a) promote health through co-designing meaningful and personally motivating activities, and (b) develop the participant's autonomy, self-responsibility and interoceptive awareness. Participants proposed activities they liked to do or would like to try. Personal trainers also suggested activities that could be meaningful and motivating for the participant, not only those based on cyclic or repetitive movements (Almarcha et al., 2021). For example: playing with their kids, doing outdoor activities, playing exergames, stretching at the office, and using the bicycle for displacement, among others.

Standardized exercise program based on World Health Organization recommendations

It consisted of cycling or running exercises, performed 5 days per week at low intensity or 3 days per week at vigorous-intensity with a minimum duration of 25–30 min per session, according to the WHO guidelines (World Health Organization [WHO], 2019). The strength training consisted of a 12-station High-intensity circuit (Klika and Jordan, 2013) performed twice a week according to the American College of Sports Medicine Guidelines (ACSM) (Bushman, 2020). All exercises could be done with bodyweight in almost any setting (e.g., home, office, hotel room, etc.). Exercises were performed for 30 s, with 10 s of transition time between bouts. The total time for the entire circuit workout was approximately 7 min. The circuit could be repeated 2–3 times. Load intensity and volume were adjusted weekly to keep a rate of perceived exertion (Borg CR 10 Scale) of 3–5 in all sessions (see **Table 1**).

TABLE 1 Comparison of the characteristics of the exercise program based on WHO recommendations and the co-designed intervention.

Type of program	WHO exercise program (WHO)	Co-designed intervention (CoD)
Foundation	WHO and ACSM guidelines	Co-designed
Exercise	Repetitive	Varied
Frequency	Aerobic: 5 d/w Strength: 2 d/w	5 d/w
Intensity	Aerobic: RPE (CR 10): 3–5 Strength: RPE (CR 10): 8	RPE (CR 10): 3–5
Duration	300 min/week	300 min/week
Type of activity	Aerobic (running, cycling), strength	Based on individual preferences

Testing

A cardiorespiratory exercise test and two questionnaires (see below) were administered pre-and post-intervention, and a personal interview was performed at the end of the intervention. The cardiorespiratory exercise test was supervised by medical staff that confirmed the health status of the participants. The questionnaires were responded online using Google Forms, and an external researcher performed the personal video conference interviews.

Cardiorespiratory exercise test

An incremental cycling test (Excalibur, Lode, Groningen, Netherlands) starting at 50 W and increasing the workload by 30 W/min until reaching a subjective rate of perceived exertion (CR-10 scale) of "very hard" (RPE $\geq$ 8) was performed. Participants breathed through a valve (Hans Rudolph, 2700, Kansas City, MO, United States), and the respiratory gas exchange was determined using an automated open-circuit system (Metasys, Brainware, La Valette, France). Oxygen and CO2 content and airflow rate were recorded breath by breath. An electrocardiogram (ECG) was continuously monitored (DMS Systems, DMS-BTT wireless Bluetooth ECG transmitter and receiver, software DMS Version 4.0, Beijing, China). The test was performed in a well-ventilated lab; the room temperature was 23°C and the relative humidity 48%, with variations of no more than 1°C in temperature and 10% in relative humidity. The tests were carried out at least 3 h after a light meal, and participants were instructed not to perform vigorous physical activity for 72 h before testing.

Questionnaires

Depression, Anxiety and Stress scales (DASS-21)

The Spanish version of the DASS-21 questionnaire (Bados et al., 2005) assessed the self-reported negative emotional states during the last week. This questionnaire contains 21 statements rated on a four-categories of Likert scale (from 0 = "does not apply to me at all" up to 3 = "it applies a lot to me most of the time"), distributed along with three subscales (with seven items each): Depression, Anxiety and Stress (Lovibond and Lovibond, 1995). The depression scale assesses dysphoria, hopelessness, devaluation of life, lack of interest/involvement and inertia (e.g., I was unable to become enthusiastic about anything). The anxiety scale assesses autonomic arousal, skeletal muscle effects, situational anxiety, and subjective experience of anxious affect (e.g., I was aware of the action of my heart in the absence of physical exertion). The stress scale is sensitive to levels of chronic non-specific arousal. It assesses difficulty relaxing, nervous arousal, and being easily upset/agitated, irritable/over-reactive and impatient (e.g., I was intolerant of anything that kept me from getting on with what I was doing).

Scores for depression, anxiety and stress are calculated by summing the scores for the relevant items. The values of Cronbach's alpha and test-retest reliability indicate good internal consistency of the Spanish version of DASS-21 (Bados et al., 2005).

Multidimensional Assessment of Interoceptive Awareness

The Spanish version of the multidimensional assessment of interoceptive awareness (MAIA) questionnaire (Valenzuela-Moguillansky and Reyes-Reyes, 2015) was administered. It is a self-report instrument developed by Mehling et al. (2012) to measure eight dimensions of interoceptive body awareness. The noticing scale assesses the awareness of uncomfortable, comfortable or neural body sensations (e.g., when I am tense, I notice where the tension is located in my body). The not distracting scale assesses the tendency not to use distraction to cope with discomfort (e.g., when I feel pain or discomfort, I try to power through it). The not worrying scale assesses the tendency to not experience emotional distress with physical discomfort (e.g., I can notice an unpleasant body sensation without worrying about it).

The attention regulation scale assesses the ability to sustain and control attention to body sensations, (e.g., I can maintain awareness of my inner bodily sensations even when a lot is going around me). The emotional awareness scale assesses the ability to attribute specific physical feelings to physiological manifestations of emotions (e.g., When something is wrong in my life, I can feel it in my body). The self-regulation scale assesses the ability to regulate distress by attention to body sensations (e.g., I can use my breath to reduce tension). The body listening scale assesses the tendency to actively listen to the body for insight (e.g., I listen to my body to inform me about what to do). The trusting scale assesses the experience of one's body as safe and trustworthy (e.g., I feel my body is a safe place). It has 32 items tested on a Likert scale, with six levels of ordinal response coded from 0 (never) to 5 (always), generating a total direct score on a scale that ranges from 0 to 160 points. The Spanish version showed appropriate construct validity and reliability indicators, with a Cronbach's α of 0.90 for the total scale and values between 0.40 and 0.86 for the different subscales (Valenzuela-Moguillansky and Reyes-Reyes, 2015).

Interviews

Participants were invited to a 30-min semi-structured video conference interview by a researcher external to the intervention to avoid bias. The semi-structured interview guides the intervention's critical points while allowing new themes/issues to emerge. The reliability of the interviews was guaranteed by the same interviewer, the same design scheme of the questions, the same length of interrogation and the same period for all interviews. The interviews were video recorded and transcribed verbatim. Two experienced qualitative researchers and five Sport Science professionals validated the interview guide before the study. It consisted of questions concerning: previous experiences, reasons for involvement in the exercise program, perceived benefits or challenges to participating, and the role of the personal trainer (e.g., Do you think the figure of the personal trainer is essential to continue with the level of physical activity achieved?) reasons to drop out/adherence, what they have learned (e.g., Have you gained resources to adapt the exercise to any personal and environmental situation?) and readiness to implement changes in their lifestyle behavior beyond the program (e.g., Have you discovered any physical activities to incorporate into your habits?).

Data analysis

Physiological testing

The ratio between the workload corresponding to the RPE $\geq$ 8 and the oxygen uptake relative to body weight (VO_2) at this workload (W/VO_2) and the ratio between the workload corresponding to the RPE $\geq$ 8 and the heart rate (HR) at this workload (W/HR) were compared pre-and post-intervention using Wilcoxon matched-pairs test and independent samples *t*-test.

Questionnaires

Means with 95% confidence intervals, medians, standard deviations, and interquartile ranges were calculated to assess the location and dispersion of scores obtained in DASS-21 and MAIA. Skewness and kurtosis were used to determine the shape and normality of the distribution of scores. Intragroup pre-post differences were evaluated using paired *t*-tests and intergroup differences through independent samples *t*-tests. Effect sizes were calculated through Cohen's d. All quantitative statistical analyses were conducted using SPSS (version 25, IBM Corp).

Interviews

All interview transcripts were cross-checked with video recordings to ensure accuracy. Identification codes were assigned [WHO, CoD or NC -non-completer-, with consecutive numbers (e.g., CoD4)]. Thematic analysis was employed to identify emergent themes until saturation was reached (Braun and Clarke, 2006). Two researchers independently reviewed one transcript to identify codes using NVIVO software (version 2, QRS International Pty Ltd). Then, they discussed the findings and presented the proposed principles derived from the data to the research team until consensus was reached on the final regulations.

Results

Physiological testing

No differences in W/VO_2 and W/HR were found pre-post intervention in both groups (WHO and CoD) nor between groups.

Questionnaires

All participants responded to DASS-21 and MAIA questionnaires, but only 13 of them completed the intervention (CoD = 8, WHO = 5).

Depression, anxiety and stress levels

DASS questionnaire descriptives are presented in **Table 2**. After the intervention, the CoD group improved their scores in the three dimensions of the DASS-21 questionnaire: depression [$t(7) = 7.907$, $p = 0.0001$], anxiety ($t = 27.032$, $p = 0.0001$) and stress ($t = 8.973$, $p = 0.0001$). However, no differences were detected in the WHO group. Intergroup differences showed higher anxiety (W = 36.000, Z = −3.038, $p = 0.002$, d = 0.84) and stress (W = 39.500, Z = −2.449, $p = 0.011$, d = 0.68) in the WHO group compared to the CoD group.

Interoceptive awareness

MAIA questionnaire descriptives are presented in **Table 3**. After the intervention, the CoD group improved in 7 of the 8 scales of the MAIA questionnaire: noticing [$t(7) = -1.276$, $p = 0.0001$], not-distracting [$t(7) = -4.492$, $p = 0.003$], attention regulation [$t(7) = -26.839$, $p = 0.0001$], emotional awareness [$t(7) = -13.642$, $p = 0.0001$], self-regulation [$t(7) = -13.316$, $p = 0.0001$], body listening [$t(7) = -7.848$, $p = 0.0001$], trusting [$t(7) = -10.991$, $p = 0.0001$] except for not-worrying [$t(7) = -1.276$, $p = 0.243$]. In the WHO group, differences were detected only in 3 scales, self-regulation [$t(4) = 4.376$, $p = 0.012$], body listening [$t(4) = -6{,}144$, $p = 0.004$], and trusting [$t(4) = -6{,}364$, $p = 0.003$].

Post intervention inter-groups differences were observed in noticing (W = 20.500, Z = −2.140, $p = 0.030$, d = 0.59), non-distracting (W = 18.500, Z = −2.442, $p = 0.011$, d = 0.68), attention regulation (W = 16.000, Z = −2.789, $p = 0.003$, d = 0.77), self-regulation (W = 15.000, Z = −2.956, $p = 0.002$, d = 0.81), listen to body signals (W = 15.000, Z = −2.952, $p = 0.002$, d = 0.82) and trust (W = 15.000, Z = −3.029, $p = 0.002$, d = 0.84) in favor of the CoD group.

Interviews

All participants were interviewed, including those who did not complete the entire intervention. The thematic analysis

TABLE 2 DASS questionnaire items descriptives.

	Group	*N*	Mean	*SD*	Variance	Skewness	SE	Kurtosis	SE
PRE_Depression	CoD	8	12.250	4.46	19.93	1.0261	0.752	−0.234	1.48
	WHO	5	8.400	7.80	60.80	1.9861	0.913	3.948	2.00
POST_Depression	CoD	8	1.500	1.41	2.00	0.4041	0.752	−0.229	1.48
	WHO	5	6.000	4.24	18.00	−0.5238	0.913	−0.963	2.00
PRE_Anxiety	CoD	8	13.000	1.51	2.29	−1.3229	0.752	0.875	1.48
	WHO	5	9.200	5.93	35.20	−0.8849	0.913	1.449	2.00
POST_Anxiety	CoD	8	0.750	1.04	1.07	0.6441	0.752	−2.240	1.48
	WHO	5	10.000	2.45	6.00	1.3608	0.913	2.000	2.00
PRE_Stress	CoD	8	17.750	4.83	23.36	−0.5353	0.752	−0.744	1.48
	WHO	5	8.800	5.76	33.20	−0.0376	0.913	−1.804	2.00
POST_Stress	CoD	8	4.000	3.02	9.14	0.3307	0.752	−1.488	1.48
	WHO	5	14.400	9.42	88.80	1.4646	0.913	2.443	2.00

TABLE 3 MAIA questionnaire items descriptives.

	Group	*N*	Mean	*SD*	Variance	Skewness	SE	Kurtosis	SE
PRE_Noticing	CoD	8	1.91	0.7063	0.4989	−0.7578	0.752	2.4997	1.48
	WHO	5	2.10	0.5477	0.3000	1.5310	0.913	1.7448	2.00
POST_Noticing	CoD	8	4.25	0.7440	0.5536	−1.2140	0.752	1.5595	1.48
	WHO	5	4.55	0.4472	0.2000	−0.0524	0.913	−2.3242	2.00
PRE_Not- distracting	CoD	8	2.92	0.3897	0.1518	1.3533	0.752	0.6000	1.48
	WHO	5	2.80	0.1807	0.0327	0.6086	0.913	−3.3333	2.00
POST_Not-distracting	CoD	8	4.08	0.6357	0.4041	−1.7759	0.752	4.0011	1.48
	WHO	5	4.27	0.4349	0.1891	−0.5215	0.913	−1.5244	2.00
PRE_ Not-worrying	CoD	8	2.08	1.3060	1.7056	0.3178	0.752	−0.1760	1.48
	WHO	5	2.20	1.3431	1.8039	1.0194	0.913	2.0429	2.00
POST_Not-worrying	CoD	8	2.59	0.3908	0.1527	−0.8853	0.752	−0.4606	1.48
	WHO	5	2.73	0.0158	2.50e-4	1.40e-14	0.913	−1.2000	2.00
PRE_ Attention regulation	CoD	8	2.10	0.5165	0.2667	0.4576	0.752	−0.4061	1.48
	WHO	5	2.08	0.6106	0.3728	−1.0217	0.913	0.6871	2.00
POST_ Attention regulation	CoD	8	4.08	0.5560	0.3091	−0.3548	0.752	−0.6512	1.48
	WHO	5	3.37	0.9125	0.8326	0.1683	0.913	−1.1433	2.00
PRE_Emotional awareness	CoD	8	2.50	0.6928	0.4800	0.2887	0.752	−0.9250	1.48
	WHO	5	3.36	0.6542	0.4280	−2.1342	0.913	4.6790	2.00
POST_ Emotional awareness	CoD	8	4.42	0.5701	0.3250	−0.3154	0.752	−1.7276	1.48
	WHO	5	4.00	1.1489	1.3200	−1.0550	0.913	0.9669	2.00
PRE_Self-regulation	CoD	8	2.16	0.6400	0.4096	0.2161	0.752	−0.1049	1.48
	WHO	5	2.60	1.3062	1.7063	0.5861	0.913	−0.3385	2.00
POST_ Self-regulation	CoD	8	4.38	0.6124	0.3750	−0.7776	0.752	−0.0571	1.48
	WHO	5	3.70	1.0216	1.0437	−0.3473	0.913	0.4149	2.00
PRE_Body-Listening	CoD	8	2.04	1.3499	1.8222	−0.0175	0.752	−0.9724	1.48
	WHO	5	1.73	0.9269	0.8591	0.2371	0.913	−0.8817	2.00
POST_ Body-Listening	CoD	8	4.12	0.6657	0.4431	−0.1099	0.752	0.0280	1.48
	WHO	5	3.67	1.1058	1.2228	−0.6821	0.913	1.1194	2.00
PRE_Trusting	CoD	8	2.58	0.6117	0.3741	0.6851	0.752	−0.4693	1.48
	WHO	5	2.73	1.3650	1.8631	1.5223	0.913	2.5324	2.00
POST_Trusting	CoD	8	4.42	0.4961	0.2461	0.4799	0.752	−2.2481	1.48
	WHO	5	4.00	1.0277	1.0561	−1.2840	0.913	2.0199	2.00

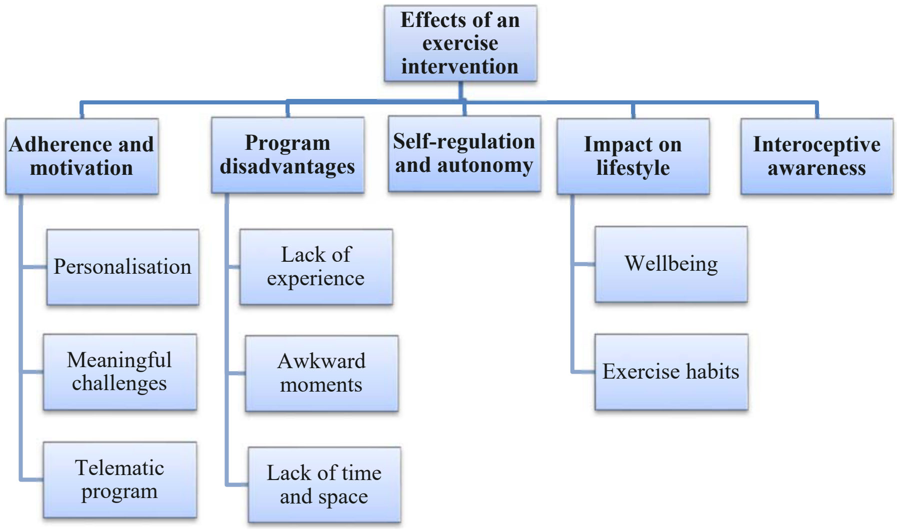

FIGURE 1
Themes and subthemes developed from the experiences of people participating in the exercise programs.

confirmed data saturation at n = 20 and revealed five themes based on the interview questions (see Figure 1).

Theme 1: Adherence and motivations during the program

Both groups concurred that being supervised by the personal trainer and receiving constant feedback facilitated their participation. Highlighting the personalization of the co-design was felt very motivating and helped to continue. They also appreciated the meaningful and novel challenges; "Not knowing what challenges the personal trainer was going to present to me next week kept me curious and motivated" (CoD8). A telematic exercise program was another widely reported benefit ""It was not necessary to go to a specific place; I could do the exercise at home during my free time" (WHO2).

Theme 2: Disadvantages of the program

Participants of the WHO group reported anxiety and stress due to their lack of experience exercising. "At the beginning, it was stressful because I am not used to it, and I did not feel fit" (NC5). As they principally exercised at home or work, they felt embarrassed when being observed by members of their families or co-workers; "I went to the bathroom to do some exercises so that my colleagues in the office could not see me" (CoD6). "During the Christmas holidays, I had my family at home, and I cared about what they could say when seeing me exercising" (NC3). The work schedule made participation difficult, and lack of time was the most reported problem in both groups; "I have little free time and find it difficult to combine exercise with family life. Physical activity is not a priority for me" (WHO4). Non-completers reported a lack of space or time to exercise; "Initially I felt very excited, but afterward it was difficult to get along and enjoy it due to my work schedule" (NC4). They dropped out of the study due to the program's lack of schedule flexibility and incompatibility; "It has been impossible for me to combine it with work and family issues" (NC6). Most participants of the CoD group, which also encountered the time barrier, succeeded in adapting to it by incorporating physical activity into their daily life in an autonomous way. "On the first day, I walked only for 30 min, but as the weeks went by, I increased the time as I felt better every day" (CoD6).

Theme 3: Self-regulation and autonomy

Participants of the CoD group adapted the exercise to their personal and environmental constraints and learnt how to self-regulate workload. "During holidays, I was not used to exercising, but this time I was able to do it because I knew the activities I could do" (CoD2) and "Being able to self-manage the activity's intensity and duration helped me do much more than I thought at first" (CoD2). They did not perceive the figure of the coach as essential due to the learnt autonomy "As time passed I was able to decide daily which activities were suitable and which not" (CoD1). The WHO group did not report self-regulation and autonomy capacities. "Although I was stressed by work, I did the series and repetitions of the strength workout I had to do" (WHO5). Non-completers found it challenging to decide on the exercise program and considered they were assuming too much responsibility; "It is impossible for me to self-regulate the intensity and the type of activity because I am always so tired that I would never do anything" (NC2).

Theme 4: Impact on lifestyle

The CoD group increased self-awareness and wellbeing: "I notice that when I walk, I get less tired, and I also notice fewer arrhythmias from the program's start" (CoD6). Many discussed their plans for exercising due to their wellbeing and trust "I feel good about myself and my body" (CoD5). Also, some of them have hired a personal trainer to continue exercising; "I have decided to continue with a personal trainer to try new different activities that I have always wanted to try" (CoD7). Other participants expressed having gained body awareness "I am now more aware of the physical activity I do in my daily life, and how I feel during and after doing it" (CoD2). "I am still exercising, incorporating my trainer's principles" (CoD3).

The WHO group also planned to change their habits by joining a gym where finding the required material. "I have decided to join a gym to access more material; it is easier for me to follow exercise routines" (WHO5). In line with the results of the questionnaires, "I have found that exercise helps reduce my anxiety and stress levels" (WHO3).

Theme 5: Interoceptive awareness

While the WHO group linked the intervention to their physical fitness, the CoD group linked it to multiple dimensions and a more general wellbeing state: "For me, health is more than a physical state. It is about being comfortable with yourself and knowing how to listen to your body to adapt to different contexts" (CoD7). Both groups stated that they had never been asked about their body state and sensations towards exercise. However, only the CoD group mentioned they had improved their interoceptive awareness; "I can recognize inflammatory states in my body based on stress, what I have eaten or what I have slept" (CoD5). "When I am nervous, I cannot trust my body signals" (WHO2).

Overall, 13 out of 20 participants were satisfied with the exercise program. However, only participants of the CoD group would recommend the program to other people; "Thanks to the constant dialogue with the personal trainer and trying different proposals, I have discovered the types of activities that work for me. Actually, I have incorporated it as a daily habit" (CoD3); while others would have preferred daily monitoring and comprehensive training planning; "I prefer to have a programmed exercise routine with technique instructions" (CoD7).

Discussion and conclusion

This study contrasts the effects on mental health and interoceptive awareness of co-designed exercise interventions and prescribed exercise programs based on the WHO recommendations for healthy adults. The co-designed intervention, aiming to guide participants from dependency to autonomy, promoted further mental health and interoceptive awareness, crucial aspects of cognitive and emotional wellbeing.

In alignment with previous research, the current study supports that exercise benefits mental health in adult population (Carek et al., 2011; Rebar et al., 2015; Bernstein and McNally, 2018). However, in this study, only participants of the CoD group reduced depression, anxiety and stress levels after the intervention. The duty to follow the program (i.e., "to take the exercise pill"), trying to comply strictly with WHO guidelines and following the exact doses contributed to increased anxiety and stress levels in some participants of the WHO group, These adverse effects have not been observed in participants performing new and challenging activities (González-Cutre et al., 2019).

In addition, only the CoD group expressed the wish to continue the intervention in the future. This can be explained by the positive affective valence reported during and after exercise by this group (Ekkekakis et al., 2011). In contrast, the emotional experience of the WHO group was not helping to introduce changes in their daily routine, as found in previous works (Kwan and Bryan, 2010; Antoniewicz and Brand, 2016). The pressure to follow a fixed exercise program, independently of daily constraints (e.g., holiday periods, family visits, amount of work), and the lack of novelty in the exercise routine may explain such results (Cao et al., 2021). As confirmed through the interviews, the five WHO participants who dropped out of the intervention reported getting overwhelmed when they could not comply with the prescribed routine and feel bored for doing the same type of exercise. Monotony seems a crucial factor contributing to low physical activity participation (Dalle Grave et al., 2011). Even active individuals engaged in the same exercise over time can reduce their motivation to the practice because of boredom (Lakicevic et al., 2020).

Enjoyment and interest seem determinant for ensuring long-term engagement (Argent et al., 2018) and adherence to exercise, leading ultimately to better health (Jekauc, 2015; Lakicevic et al., 2020). For example, performing similar physical activities in groups or virtual reality environments (e.g., exergaming approach) can create a distraction from negative thoughts related to exercise and encourage participation (Molina et al., 2014). Other authors propose an agreement between the athlete-trainer on goals and the selection of exercises to fit the athlete's needs, motivations, and abilities (Wackerhage and Schoenfeld, 2021). Some results have shown more outstanding fitness scores and affective responses when participants self-selected exercise conditions (Parfitt et al., 2006) or when designing their exercise program based on their previous knowledge instead of following a standardized exercise program (Papadakis et al., 2021).

Decisions to engage in regular physical activity are also influenced by participants' expectancies (Loehr et al., 2014). It is worth pointing out that the two CoD participants dropping out during the intervention expected to get involved in a standardized training program to become stronger. The literature refers to previous interventions, based on the SDT (Deci and Ryan, 2013), for increasing the motivation and adherence of patients to exercise treatments. Positive effects on adaptive motivational processes, quality of life and wellbeing have been reported (Duda et al., 2014). In fact, when participants self-paced or chose their mode of exercise, have more positive affective responses and autonomy than when they follow exercise prescriptions (Parfitt and Gledhill, 2004).

Although both (SDT practices and CoD intervention) consider participants' motivations and preferences, the CoD goes a bit further, proposing a change of roles: participants and professionals co-design and co-adapt continuously unique and personalized protocols to develop participants' self-knowledge and autonomy. That is, the initial program may evolve during the intervention due to the need of co-adapting to the multiple personal and environmental constraints affecting the process. For instance, a participant evolved from proposing home-based exercises to open-air activities in family and activities in nature (e.g., climbing mountains, trekking, etc.).

As confirmed through the interviews, the role of exercise co-designers developed in the CoD group self-knowledge, self-regulation, and autonomy. These potentially beneficial learning effects can also be associated with rewarding experiences (Fisher and Yarwood, 2008; Leckey, 2011). Being less dependent on the personal trainer, facilities and equipment, they could potentially create a larger adaptivity and guarantee a longer adherence to exercise. As they could choose the physical and social environments for exercising (e.g., in a park, in the mountains, with family, or friends), they could explore different exercise modalities, experience the most contextually adequate, and become more aware of their wellbeing and health.

It is worth pointing out that the commonly prescribed exercise for the adult population, converging on aerobic and strength programs and adhering to WHO recommendations, is based on oversimplified theoretical and methodological assumptions, as the possibility to transfer to individuals results obtained by comparing group data means (Balagué et al., 2020b). The network physiology of exercise conceptualizes the human organism as a complex adaptive system embedded and in constant interaction with social and policy factors (Bauman et al., 2012). Assuming there is no unique way to promote a healthy state (Sturmberg et al., 2019), some authors propose co-designing contextually sensitive, meaningful, motivating, and self-regulated exercise programs (Balagué et al., 2020a). However, as far as we know, few attempts have been made to contrast the emotional benefits of different exercise interventions (Hogan et al., 2015).

Concerning the interoceptive awareness effects, the light results obtained in the MAIA questionnaire by the WHO group (improving only in three of the eight scales), compared to the CoD group (seven of eight), can be explained by the lack of emphasis on the WHO intervention on interoceptive awareness and the aforementioned stressful experiences of participants. Stressed individuals show difficulties regulating emotional responses because they stopped trusting and listening to body signs (Price and Hooven, 2018). In contrast, the CoD group improved in seven of the eight scales and had fewer difficulties adapting the exercise type and characteristics to their personal and environmental constraints. An exciting outcome of performing novelty, motivating and challenging activities is the deep level of engagement which can lead to flow experiences (Swann et al., 2019; Montull et al., 2020), which increase autonomous motivation, reduces boredom, and relates to future involvement (Csikszentmihalyi, 2020).

Recent sports-related research has highlighted the need to develop early education programs to enhance interoceptive awareness (Montull et al., 2022). Our results show that a co-designed type of intervention may help to develop this relevant property. Unfortunately, no studies have tested the potential benefits of interoceptive awareness and self-knowledge on fitness states. We hypothesize a circular causality between both variables that need to be explored.

This research has some potential practical implications for future exercise interventions in adult population: (a) meaningful, motivating, and enjoyable activities may produce more psychological benefits than universal exercise recommendations, and lead to further exercise adherence, (b) initial exercise programs should be co-adapted to the changing personal and environmental constraints, not the other way around, (c) practitioners perceptions and interoceptive awareness should be developed to help on selecting adequately the type and characteristics of exercise and be the basis for workload adaptation. In turn, health professionals and personal coaches should: (a) be aware of the limitations of current exercise guidelines and be educated on co-designing instead of prescribing exercise, (b) lead practitioners from dependency to autonomy providing training criteria instead of exercise receipts, (c) contribute to the development of interoceptive awareness to prevent injuries, detect deleterious training effects (e.g., like overtraining) and promote a multidimensional fitness state (Almarcha et al., 2021).

It is recommendable to investigate the effects of co-designed exercise interventions on other populations like chronic patients and different age groups. In addition, a gender analysis, which was impossible to implement in this research due to the small number of participants, is also warranted.

It was expected to find more noticeable physiological effects of the intervention in the WHO group because participants were tested through cycle ergometers. While cycling was recommended in the aerobic training routines of the WHO group, the CoD group did not specifically practice cycling. Due to the low sample, no significant differences were found in cycling performance and physiological associates either inter or intra-groups. Further research is warranted to study the long-term effects of this type of intervention.

In conclusion, a co-designed exercise intervention was more effective for developing mental health, interoceptive awareness, autonomy, and exercise self-regulation in healthy adults than the prescription of an exercise program based on the universal recommendations of the WHO.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: doi: 10.6084/m9.figshare.19767163.v1.

Ethics statement

The studies involving human participants were reviewed and approved by Comité d'Ètica d'Investigacions Clíniques de l'Administració Esportiva de Catalunya (ref. 07/2015/CEICEGC). The patients/participants provided their written informed consent to participate in this study.

Author contributions

MA, NB, and CJ contributed to the conception and design of the study. MA and IG organized the database and wrote the first draft of the manuscript. MA performed the statistical analysis. MA and NB wrote the final manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

This work was supported by the National Institute of Physical Education of Catalonia (INEFC), Generalitat de Catalunya. MA was supported by the project "Toward an embodied and transdisciplinary education" granted by the Ministerio de Educación y Formación Professional of the Spanish government (FPU19/05693).

Acknowledgments

We thank all the volunteer participants and INEFC students who have made this experience possible.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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TYPE Original Research
PUBLISHED 02 August 2022
DOI 10.3389/fnbeh.2022.884490

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Emotion Regulation and Processing, a section of the journal Frontiers in Behavioral Neuroscience

RECEIVED 26 February 2022
ACCEPTED 24 June 2022
PUBLISHED 02 August 2022

CITATION
Zheng K, Deng Z, Qian J, Chen Y, Li S and Huang T (2022) Changes in working memory performance and cortical activity during acute aerobic exercise in young adults.
Front. Behav. Neurosci. 16:884490.
doi: 10.3389/fnbeh.2022.884490

Changes in working memory performance and cortical activity during acute aerobic exercise in young adults

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This study aimed to examine the concurrent performance of working memory and cortical activity during acute aerobic exercise in young adults. In a crossover study design, 27 young adults (mean age = 22.7 ± 3.4 years, 15 women) participated in two experimental conditions in a randomized order: (1) sitting condition (without exercise) and (2) cycling condition (moderate-intensity exercise). Working memory was measured with a modified version of the n-back task. A functional near-infrared spectroscopy (fNIRS) was used to measure cortex activation. In the cycling condition, response time (RT) for the n-back task was significantly faster ($p < 0.05$). No differences in accuracy were observed between the sitting and cycling conditions. The fNIRS results showed that the oxygenated hemoglobin (oxy-Hb) concentrations in the bilateral frontopolar area ($p < 0.05$), dorsolateral prefrontal cortex ($p < 0.05$), and right premotor and supplementary cortex ($p < 0.05$) were decreased while cycling. The findings indicated that the concurrent performance of working memory was improved during acute aerobic exercise, whereas cortical activity was decreased in some brain regions.

KEYWORDS

exercise, working memory, cortical activity, fNIRS, young adults

Introduction

Working memory is not only crucial to scholastic performance in childhood (Hitchcock and Westwell, 2017; Spiegel et al., 2021), but it is also linked with mental health in adulthood (Nikolas et al., 2019; Morales-Munoz et al., 2021) and successful aging (Bosnes et al., 2022). The prefrontal cortex (PFC) plays an important role in modulating higher-level functions such as working memory (Robbins and Arnsten, 2009; McGuire and Botvinick, 2010). Previous studies have shown that chronic exercise may improve working memory over the lifespan (Padilla et al., 2014; Xue et al., 2019; Liu et al., 2020; Ludyga et al., 2022). Few studies have assessed working memory performance during acute exercise. Clarifying how working memory performance is influenced during physical exertion has practical implications. For instance, successful sports performance, especially in open-skill exercise, highly depends on the ability to exercise concurrently while undergoing cognitive demands (Davranche et al., 2005). Similarly, some high-stress occupations (e.g., firefighter or military personnel) involve higher-order cognitive processes (e.g., working memory) while simultaneously engaging in physical efforts (Stone et al., 2020).

Arousal level may be associated with cognitive performance (Lambourne and Tomporowski, 2010; Munn et al., 2021). An optimal level of arousal may be induced by moderate-intensity exercise, thereby enhancing cognitive performance (Brisswalter et al., 2002; Tomporowski, 2003). Meanwhile, according to catecholamine hypothesis of exercise-cognition interaction, moderate-intensity exercise may facilitate cognitive performance (McMorris, 2021). However, existing studies yielded mixed findings regarding working memory performance during exercise. For instance, Martins et al. (2013) and Komiyama et al. (2017) found that working memory performance was improved during moderate-intensity exercise in young adults. In contrast, Audiffren et al. (2009) and Lambourne et al. (2010) suggested that working memory performance was maintained at the same level.

Most of the aforementioned studies were limited to behavioral measurements, whereas the cognitive task-evoked cortical activity associated with working memory during exercise was unclear. Previous neuroimaging studies, primarily using functional magnetic resonance imaging (fMRI) (Ding et al., 2021; Domingos et al., 2021) and electroencephalogram (EEG) (Chang et al., 2017; Silveira et al., 2019; Wu et al., 2019), have examined cognitive task-evoked neural activation after exercise intervention. However, the in-task cortical activity during exercise was less investigated. The neuroimaging technique functional near-infrared spectroscopy (fNIRS) provides non-invasive, portable measurements of cortical activation. It is relatively robust with motion artifacts, so it can be used to measure cortical hemodynamics under physically demanding conditions (Tempest and Reiss, 2019). Some available fNIRS studies suggested that cortical activation pattern changed when conducting cognitive tasks during exercise. One of our previous studies (Huang et al., 2019) examined the effects of self-paced low-intensity cycling on inhibitory control, cognitive flexibility, and cortical activation in young adults. The fNIRS results showed that the cycling condition resulted in lower oxygenated hemoglobin (oxy-Hb) concentrations associated with the Stroop interference effects in some PFC regions. In contrast, oxy-Hb concentrations associated with global switch costs were higher during cycling. An fNIRS study by Tempest and Reiss (2019) found that increased activation of the PFC associated with a working memory task during cycling. Therefore, further studies are needed to investigate the cognitive task-evoked cortical activity during exercise.

Taken together, changes in working memory performance and underlying cortical activation patterns during acute aerobic exercise remain unclear. Therefore, the purpose of this study was to investigate the performance of working memory and task-evoked cortical activity during acute aerobic exercise.

Methods

Participants

Twenty-nine right-handed young adults voluntarily took part in this study. All the participants were recruited from Shanghai Jiao Tong University. No participants reported any cardiovascular diseases, mental illnesses, or neurological disorders. They were provided with informed consent forms before the experiment and full information on the protocol of the study. The protocol was reviewed and approved by the ethical committee of Shanghai Jiao Tong University (ethical code: H2020042I).

Sample size was determined using the G*Power software (Faul et al., 2007). Statistical power and sample size calculations ($\alpha = 0.05$, $1\text{-}\beta = 0.80$) were performed based on the effect size (Cohen's $d = 0.55$) of the study by Tempest and Reiss (2019). A total of 18 participants were required to achieve a power of 80% to detect a significant within-group difference. Finally, 29 participants volunteered to participate in this study. Two participants were excluded from data analyses because of non-compliance with the behavioral measurement, yielding a final sample of 27 participants (mean age 22.7 ± 3.4 years, 15 women). Additionally, six participants were discarded from the fNIRS analysis because of insufficient signal quality, resulting in 21 participants for the fNIRS analysis.

Experimental protocols

This study used a randomized crossover design. The participants visited the laboratory on three separate occasions. On the first visit, the participants' handedness was verified using a validated Chinese version of the Handedness questionnaire (Li, 1983). The participants completed a physical activity readiness questionnaire (PAR-Q) to ensure safety for the following assessment. In an incremental cycle ergometer test (Ergomedic 839E; Monark Exercise AB, Varberg, Sweden), maximal aerobic power (MAP) was measured in order to determine the individual exercise workload of the following moderate-intensity exercise protocol (50% MAP). An initial workload of 25 W was set, and the workload was gradually increased by 25 W every 2 min. The participants were advised to remain at or above 60 revolutions per minute (RPM) throughout the test. After exhaustion or when a participant could not maintain 60 RPM, the test was terminated. Heart rate (HR) was determined using a Suunto heart rate monitor (SuuntoM5; SUUNTO Inc., Vantaa, Finland). The Borg Rating of Perceived Exertion (RPE) Scale was used to measure self-perceived physical exertion (Borg, 1998). HR and RPE were recorded following each increment. The participants were verbally encouraged to achieve their maximum level, particularly once they reported an RPE of 17 or higher.

$$W_{max} = W_{com} + \frac{t}{120} * 25, \quad (1)$$

MAP (W_{max}) was calculated with the equation above (Kuipers et al., 1985), where W_{com} represents the load of the last completed stage, and t (second) represents the time of the last incomplete stage. There was a 48-h interval between the MAP test and the first experimental session. The next two visits involved the sitting condition (without exercise) and the cycling condition (moderate-intensity exercise), which were conducted with a counterbalanced measure design (Figure 1A). Each condition occurred 7 days apart but at the same time of the day. For the cycling condition, the total duration consisted of 15 min of exercise on a cycle ergometer. The exercise began with a 3-min warmup in which the participants reached the desired steady-state heart rate (∼64–76% HR_{max}). Then, the participants were required to maintain this intensity throughout the n-back task. The n-back task was performed at the fourth minute following the onset of exercise and lasted ∼8 min. There was a 15-s "cognitive rest" interval between each block during which the participants continued to cycle. Finally, there was a 3-min active rest at a 30-W workload to bring the total cycling time to 15 min for each participant. The participants' HR and cortical activation were continuously monitored throughout the test. RPE and arousal levels were recorded immediately after exercise. The sitting condition used a similar procedure. The participants were required to perform the n-back task when sitting on the cycle ergometer without cycling. It is noteworthy that the sitting condition was shorter than the cycling condition because there was no warmup and an active-rest period.

Psychological measures

The Felt Arousal Scale (FAS) was adopted to measure arousal level changes (Svebak and Murgatroyd, 1985). The scale ranges from 1 (low arousal) to 6 (high arousal). In this study, the participants were asked to rate their present psychological state before and immediately after the experimental conditions (pre and post-sessions).

n-back paradigm

This study employed modified versions of the n-back task (Kao et al., 2020), a well-known paradigm for investigating working memory. The task was programmed and presented with the E-Prime 3.0 software (Psychology Software Tools Inc., United States). The number of stimuli (between 3 and 8) was displayed in the center of the screen (Figure 1B). The n-back task consisted of eight blocks of 96 trials. Each block included 12 trials (four target and eight non-target trials) presented in a pseudorandomized order. In each trial, a single number was presented in the center of a computer screen for 200 ms, followed by an inter-stimulus interval (ISI) of 2,300 ms. The participants should respond within 1,000 ms. Responding with a left-hand press ("F" key) was required when the current stimulus matched the stimulus from n-steps earlier in the sequence (i.e., target), and with the right-hand press ("J" key) when the current stimulus did not match the n steps earlier in the sequence (i.e., non-target). For instance, in the 2-back task condition, the participants were required to use their left hand to respond to the same number presented two trials earlier, and with their right hand to respond to all other numbers. Each task block began with a 5-s cue that informed of the following task condition, and the task blocks were separated with 15-s resting periods. Each task block lasted 35 s, and the whole session lasted ∼8 min. The participants were required to respond as quickly and accurately as possible. Response time (RT) and accuracy were recorded. An initial practice block was administered with 1-back and 2-back conditions before the experiment commenced to ensure that the participants understand the task.

fNIRS measurement

During the two experimental conditions, cortical hemodynamic changes were monitored using a multi-channel continuous-wave fNIRS system (NIRSport 2; NIRx Medical Technologies, United States) at a sampling rate of 6.78 Hz. The montage setup consisted of 12 dual-wavelength (760 and 850 nm) source probes, and 12 optical detector probes covered several 10–10 electroencephalography positions. By arranging the 12 sources and the 12 detector probes alternately at a distance of 3 cm, there are 34 channels (Figure 2). The probability of estimating spatial information (Supplementary Table 1) for each channel of a brain region was determined using the probabilistic estimation method (Okamoto et al., 2004; Tsuzuki et al., 2007). Optical density data were analyzed using the modified Beer-Lambert Law to calculate signals reflecting oxy-Hb, deoxygenated hemoglobin (deoxy-Hb), and total hemoglobin (total-Hb) signal changes. Compared to deoxy-Hb and total-Hb signals, oxy-Hb signals have a higher signal-to-noise ratio (Strangman et al., 2002) and retest reliability (Plichta et al., 2006). Therefore, this study used oxy-Hb signals as indicators of regional cortex activity.

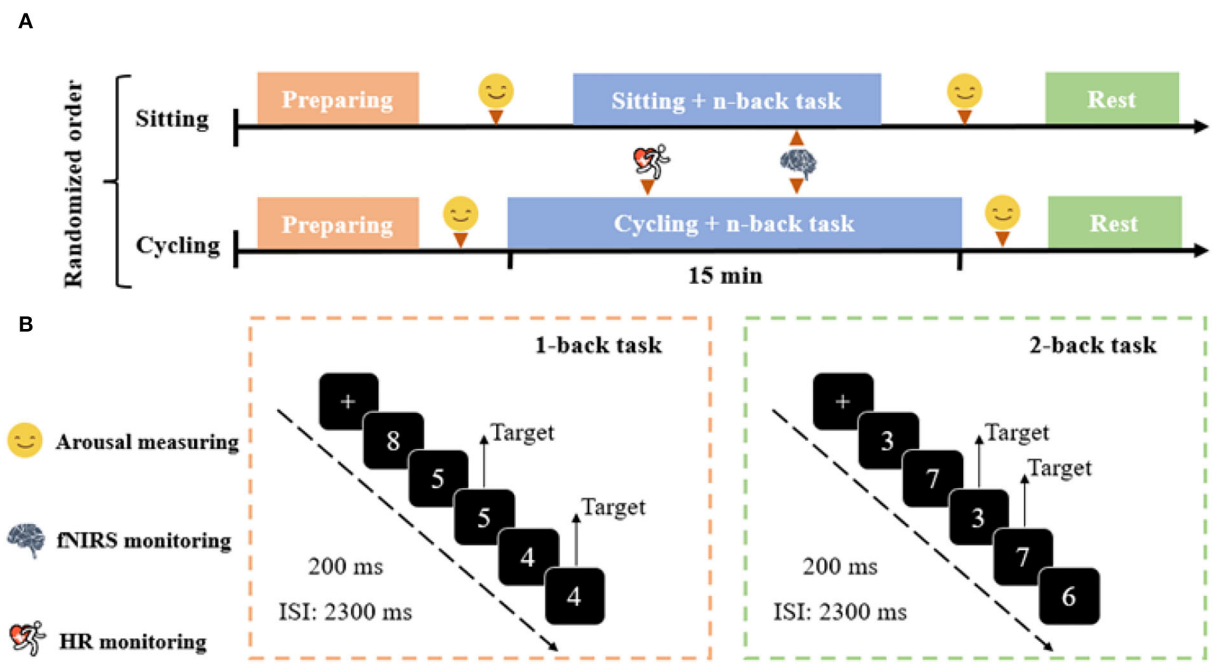

FIGURE 1
Experimental protocol. **(A)** Experimental design consisting of the sitting and cycling conditions. **(B)** Schematic illustration of the n-back task. Examples of trials for the 1-back and 2-back conditions of the n-back task are exemplified.

fNIRS data analysis

The raw data of fNIRS were preprocessed using NIRSLAB (NIRx, United States). A bandpass filter (in the 0.01 to 0.5 Hz range to remove noise like respiratory frequency, low-frequency oscillations, and Mayer waves) was applied, and the data were converted to oxy-Hb concentrations. The mean values of the oxy-Hb concentrations from the baseline (0–2 s before the onset of the trial) and the task (4–50 s after the onset of the trial) were computed for each participant, region of interest (ROI), and task condition.

In previous studies, some brain regions were activated during similar motor (bilateral motor cortex) and n-back (bilateral PFC) tasks (Tempest and Reiss, 2019). Thus, the ROIs in this study included the bilateral frontopolar area (FPA), dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), middle temporal gyrus (MTG), and pre-motor and supplementary cortex (MC) regions. For ROI definition, this study used the automated anatomical labeling atlas Brodmann (Rorden and Brett, 2000). Regions included the left (channels 1, 2, and 9–11) and right (channels 23–27) FPAs, left (channels 8, 13, and 15–17) and right (channels 19, 28–30, and 32) DLPFCs, left (channels 5–7) and right (channels 31, 33, and 34) VLPFCs, left (channels 3 and 4) and right (channels 21 and 22) MTGs, and left (channels 12 and 14) and right (channels 18 and 20) MCs (Figure 3).

Statistical analysis

Statistical analyses were performed using SPSS V.22 (IBM, Chicago, IL, United States). The RT and accuracy of the n-back task and oxy-Hb signal changes in all the ROIs were analyzed by 2 (experimental condition: sitting and cycling) × 2 (task condition: 1-back and 2-back) repeated-measures analysis of variance (RM-ANOVA). Spearman's correlation coefficients were calculated to evaluate the relationship between exercise-induced arousal and n-back task performance. Partial eta squared (η_p^2) was calculated as a measure of effect size. Statistical significance levels were set at $p < 0.05$. False discovery rate (FDR) was used to control for multiple testing for ROI-wise analyses of the fNIRS data.

Results

Physiological and psychological parameters

The changes in heart rate and arousal level are presented in Figure 4. The mean of HR and RPE in the cycling condition was 131.14 ± 11.55 beats/min (~73% HR_{max}) and 13.59 ± 1.15 points, respectively. The two physiological parameters showed that the exercise intensity of cycling condition was moderate

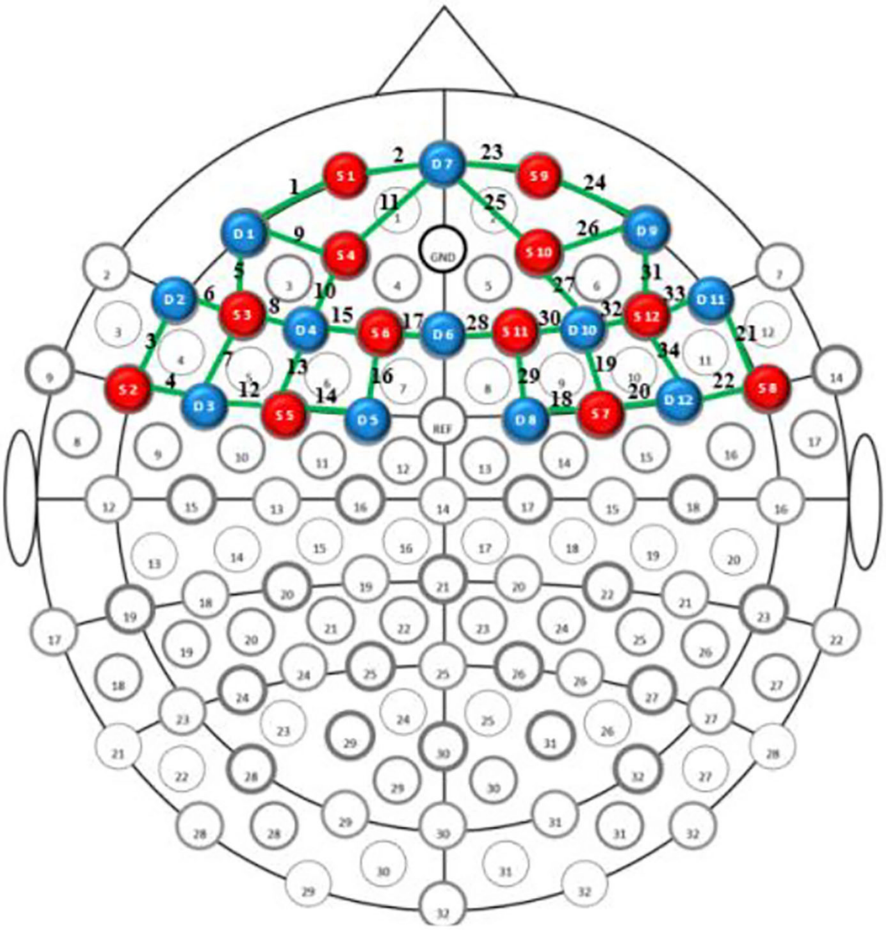

FIGURE 2
fNIRS probe layout. The red and blue circles indicate sources and detector probes, respectively. Green lines represent the nearest source-detector pairs (channels).

based on the American College of Sports Medicine (ACSM) guidelines (Garber et al., 2011).

Behavioral results

For RT, as shown in Figure 5, the RM-ANOVA revealed that the main effects of the task and experimental conditions were both significant [$F_{(1,26)} = 30.72$, $\eta_p^2 = 0.54$, $p < 0.001$, and $F_{(1,26)} = 4.78$, $\eta_p^2 = 0.16$, $p < 0.05$, respectively]. The RT of the 1-back task was significantly faster than that of the 2-back task. In the sitting condition, the RT of the 1-back task was significantly faster than that of the 2-back task (400.96 ± 29.17 ms vs. 467.3 ± 35.11 ms, $p < 0.001$). Accuracy was not significantly different between the 1-back and 2-back tasks (96.46 ± 0.74% vs. 95.74 ± 0.95%, $p > 0.05$). In the cycling condition, the RT of the 1-back task was significantly faster than that of the 2-back task (363.85 ± 24.12 ms vs. 418.48 ± 28.24 ms, $p < 0.001$). There were no significant differences in accuracy between the 1-back and 2-back tasks (95.62 ± 0.93% vs. 93.8 ± 1.23%, $p > 0.05$). The RT of the cycling condition was significantly faster than that of the sitting condition (391.17 ± 25.26 ms vs. 434.13 ± 31.56 ms, $p < 0.05$). The RM-ANOVA performed on the accuracy of the n-back task revealed that there were no significant main or interaction effects.

fNIRS results

The RM-ANOVA performed on ROI-wise oxy-Hb concentrations revealed that there were significant main effects of the task condition on r-VLPFC [$F_{(1,20)} = 6.92$, $\eta_p^2 = 0.26$, $p < 0.05$, FDR-corrected] and l-MTG [$F_{(1,20)} = 5.04$, $\eta_p^2 = 0.2$, $p < 0.05$, FDR-corrected]. The results showed that oxy-Hb concentrations were significantly greater in the 2-back task than in the 1-back task in r-VLPFC and l-MTG

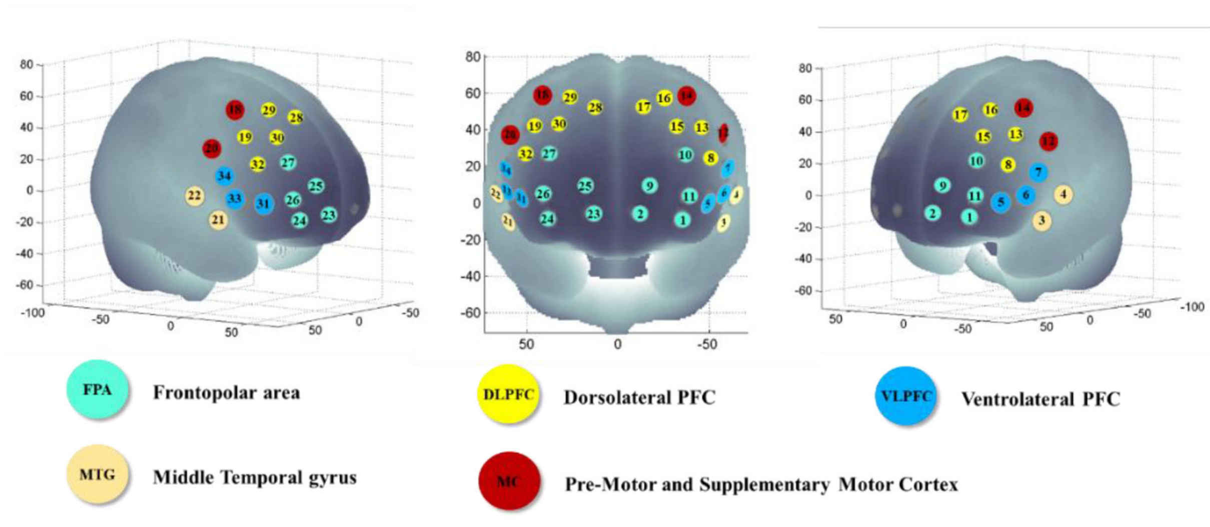

FIGURE 3
Localization of each channel, Montreal Neurological Institute (MNI) coordinates, and Brodmann areas.

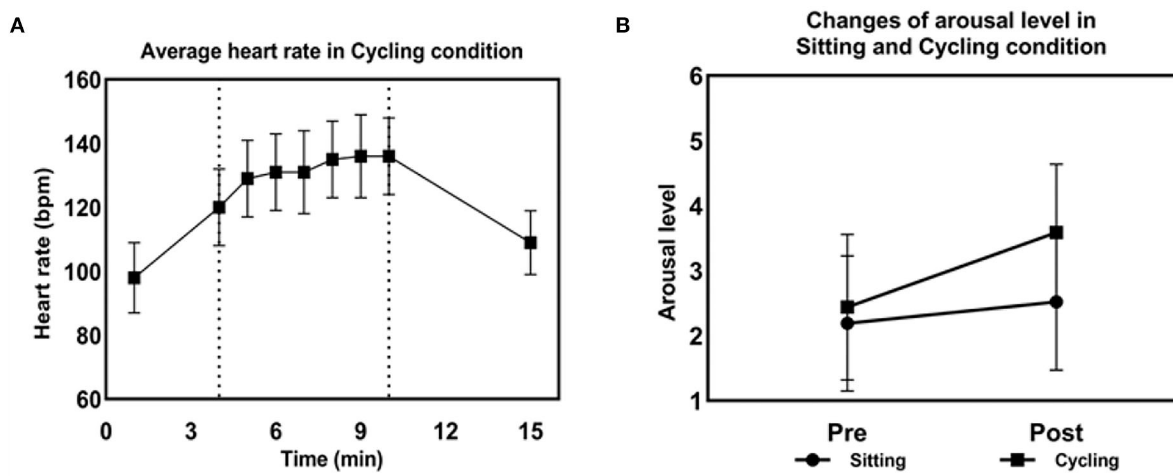

FIGURE 4
Physiological and psychological parameters during the cycling condition. **(A)** Changes in heart rate in the cycling condition. **(B)** Changes in arousal levels in the sitting and cycling condition.

(Supplementary Table 2). Also, there were significant main effects of the experimental condition on the following: l-FPA [$F_{(1,20)} = 5.79$, $\eta_p^2 = 0.22$, $p < 0.05$, FDR-corrected], r-FPA [$F_{(1,20)} = 9.38$, $\eta^2 p = 0.27$, $p < 0.05$, FDR-corrected], l-DLPFC [$F_{(1,20)} = 6.42$, $\eta_p^2 = 0.24$, $p < 0.05$, FDR-corrected], r-DLPFC [$F_{(1,20)} = 7.27$, $\eta_p^2 = 0.27$, $p < 0.05$, FDR-corrected], r-MC [$F_{(1,20)} = 5.99$, $\eta_p^2 = 0.23$, $p < 0.05$, FDR-corrected]. The results showed that oxy-Hb concentrations in the cycling condition were significantly lower than those in the sitting condition (l-FPA: 0.15 ± 0.37 vs. -1.57 ± 0.61; r-FPA: -0.11 ± 0.39 vs. -2.26 ± 0.71; l-DLPFC: 0.68 ± 0.45 vs. -0.86 ± 0.35; r-DLPFC: 0.55 ± 0.32 vs. -1.1 ± 0.54; l-MC: 0.54 ± 0.27 vs. -0.74 ± 0.52; r-MC: 0.66 ± 0.29 vs. -0.37 ± 0.43) (Figure 6). The RM-ANOVA performed on ROI-wise oxy-Hb concentrations revealed a significant interaction between the experimental and task conditions in the following: l-FPA [$F_{(1,20)} = 6.11$, $\eta_p^2 = 0.23$, $p < 0.05$, FDR-corrected], r-FPA [$F_{(1,20)} = 9.33$, $\eta_p^2 = 0.32$, $p < 0.05$, FDR-corrected], r-DLPFC [$F_{(1,20)} = 5.76$, $\eta_p^2 = 0.22$, $p < 0.05$, FDR-corrected], and r-MC [$F_{(1,20)} = 12.11$, $\eta_p^2 = 0.38$, $p < 0.05$, FDR-corrected]. The results demonstrated that oxy-Hb concentrations in response to the 2-back task in the cycling condition were significantly lower

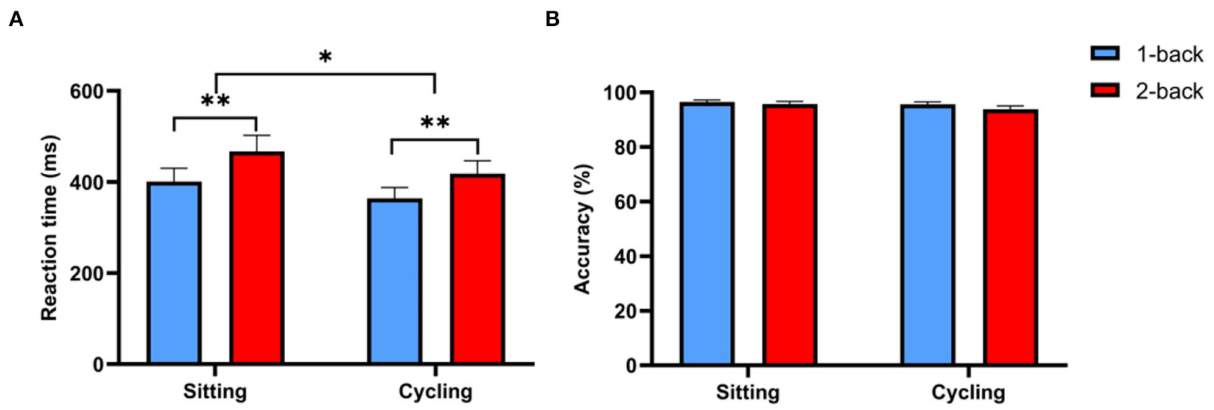

FIGURE 5
RT and accuracy of the n-back task. **(A)** Comparison of RT between the sitting and cycling conditions. **(B)** Comparison of accuracy between the sitting and cycling conditions. Data are expressed as mean ± standard error. * indicates $p < 0.05$; ** indicates $p < 0.001$.

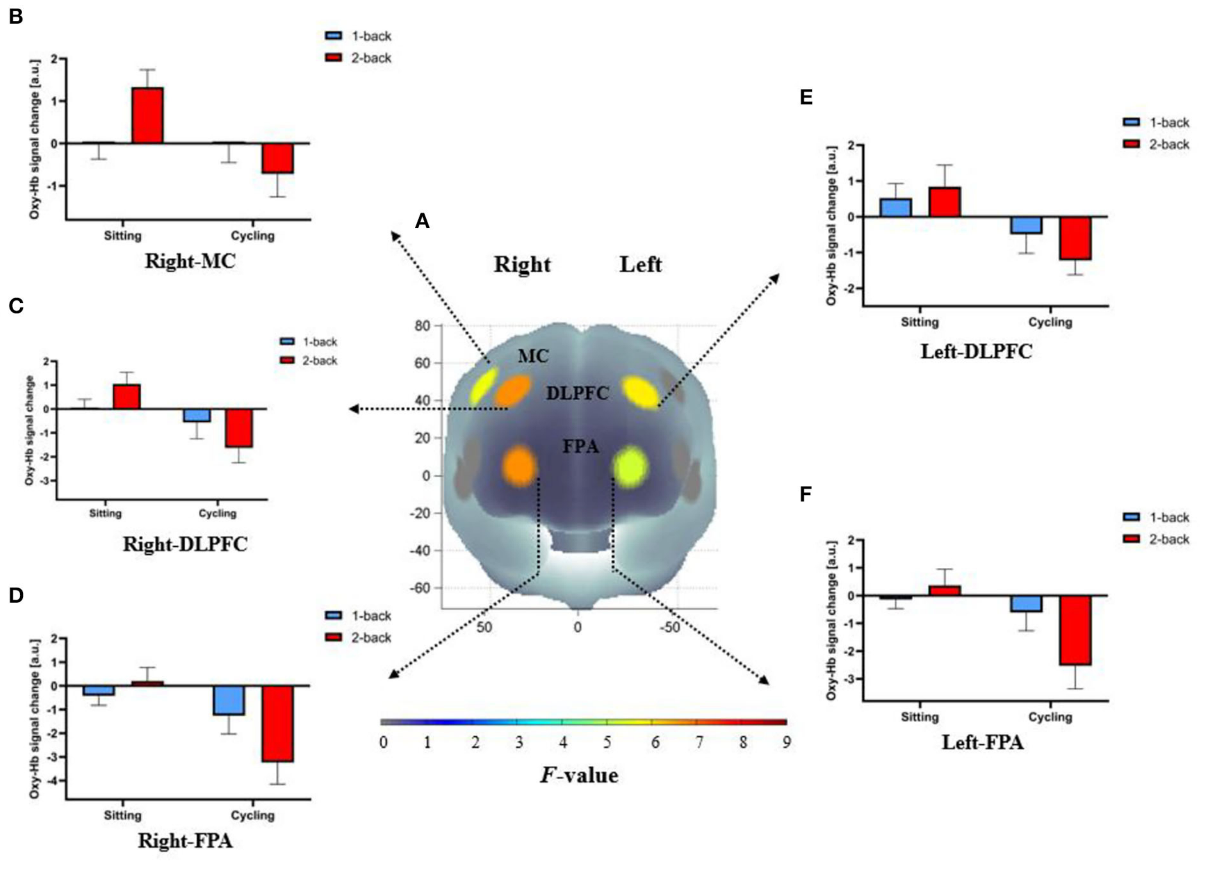

FIGURE 6
Cortical activation patterns during the n-back task in the sitting and cycling conditions. **(A)** F-map of oxy-Hb concentrations reflecting the main effect of the experimental condition. The significant main effect of the experimental condition between sitting and cycling conditions can be seen in the bilateral FPA, DLPFC, and r-MC ($p < 0.05$, FDR-corrected) among the ten regions of interest. F-values are displayed according to the color bar. **(B–F)** The mean difference of oxy-Hb concentrations between 1-back and 2-back conditions in both the bilateral FPA, DLPFC, and r-MC for sitting and cycling conditions.

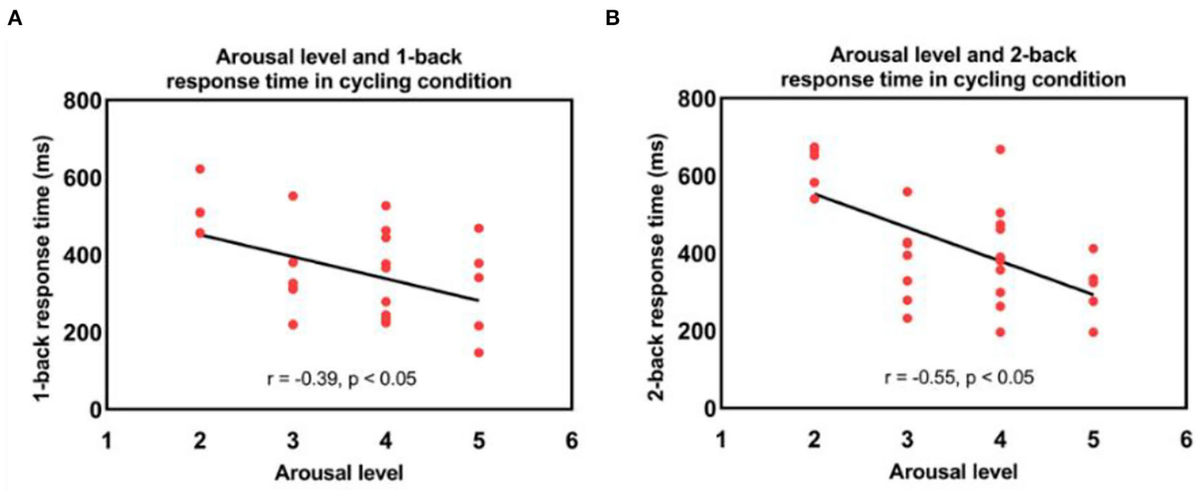

FIGURE 7
Correlations between the arousal level immediately after exercise and **(A)** 1-back and **(B)** 2-back response times in the cycling condition.

than those in the sitting condition. Oxy-Hb concentrations in response to the 2-back task in r-MC were significantly higher than those in response to the 1-back task in the sitting condition (Supplementary Tables 2, 3).

The link between exercise-induced arousal, behavioral and fNIRS results

The RM-ANOVA was conducted to examine the changes in arousal level. The results showed that there was a significant interaction between condition and session factors [$F_{(1,27)} = 9.31, p < 0.05$] and the main effects for condition [$F_{(1,27)} = 26, p < 0.001$] and the sessions [$F_{(1,27)} = 29.21, p < 0.001$]. There was no difference in pre-session arousal levels between the sitting and cycling conditions [$F_{(1,27)} = 3.58, p > 0.05$]. Furthermore, the arousal level increased significantly immediately after moderate-intensity exercise [$F_{(1,27)} = 60.09, p < 0.001$]. Post-session arousal levels for cycling were significantly higher than post-session arousal levels for the sitting condition [$F_{(1,27)} = 46.27, p < 0.001$]. In addition, 1-back and 2-back RTs were negatively correlated with exercise-induced arousal levels in the cycling condition ($r = -0.39$, $r = -0.55$, $p < 0.05$, respectively, Figure 7). The negative correlation between arousal level and RT indicated that improved working memory performance was associated with elevated level of arousal. There was, however, no significant interaction or main effect for accuracy.

To examine the association between the cycling condition-related response time shortening (1-back and 2-back) and cortical activity in the bilateral FPA, DLPFC, and r-MC, the McNemar test was adopted to assess the correspondence between the two incidences (Stegman, 1989; Yanagisawa et al., 2010). The results demonstrated that the coincidence frequencies for the bilateral FPA, DLPFC, and r-MC were not statistically significant (all $p > 0.05$). Therefore, the present results indicate that the improved working memory performance demonstrated in RT and the bilateral FPA, DLPFC, and r-MC activations were not significantly coincided.

Discussion

This study examined the concurrent performance of the n-back task and cortical activity during acute moderate-intensity exercise in young adults. It was demonstrated that the RT in the n-back task was facilitated without sacrificing the accuracy in the cycling condition. The fNIRS results indicated that, compared with the sitting condition, the cycling condition resulted in lower oxy-Hb concentrations in the bilateral FPA, DLPFC, and r-MC.

In this study, the concurrent performance of the n-back task was improved during moderate-intensity exercise, as indicated by a faster RT. Currently, only a limited number of studies have investigated the effects of exercise on the concurrent performance of working memory in young adults. Martins et al. (2013) found that the performance of the paced auditory serial addition task (PASAT) and Sternberg task performance were improved during moderate-intensity exercise. Komiyama et al. (2017) also demonstrated a positive effect on working memory measured by spatial delayed response task (Spatial DR) during moderate-intensity exercise. However, some studies observed that working memory was not changed in this exercise intensity (Audiffren et al., 2009; Lambourne et al., 2010; Komiyama et al., 2015, 2020). The discrepancy may be due to the characteristics of varied working memory tasks.

Exercise duration may also moderate the exercise-working memory relationship. For instance, some studies with a relatively short duration have shown positive effects on working memory (Martins et al., 2013; Komiyama et al., 2017), whereas no effects were observed in a relatively long duration (30 min or more) (Audiffren et al., 2009; Lambourne et al., 2010; Komiyama et al., 2015).

The arousal measured by FAS significantly increased to a moderate level during cycling. The RT of the n-back task was negatively associated with arousal level, suggesting that working memory performance improved after the rise of arousal during the exercise. Previous studies have suggested an inverted U-shaped relationship between arousal and information processing (Tomporowski, 2003; Lambourne and Tomporowski, 2010). Therefore, the current study supported that exercise-induced elevation of arousal level may, in part, account for the faster RT during the cycling condition. In addition, the catecholamine hypothesis posits that increased phasic release of dopamine and norepinephrine during moderate-intensity exercise enhances cognitive performance, which provide another plausible explanation of the processes involved in facilitating working memory performance during moderate-intensity exercise (McMorris, 2016, 2021).

Concerning the findings of fNIRS, the in-task oxy-Hb concentrations in the bilateral FPA, DLPFC, and r-MC were lower in the cycling condition, which suggested that cortical activation was reduced in those regions during the moderate-intensity exercise. The underlying mechanisms remain unclear. A motor and cognitive dual-task condition is considered more complex and requires both motor and cognitive brain resources (Maidan et al., 2021). It is plausible that simultaneously performing motor and cognitive tasks may lead to competition and reallocation of metabolic and attentional resources. Since the neural circuitry involved in initiation, control, and maintenance of movements requires considerable metabolic resources (Friedman et al., 1982; Lambourne and Tomporowski, 2010), more brain resources were reallocated in the primary motor cortex during the moderate-intensity exercise. However, it remains to be investigated why oxy-Hb concentrations were decreased in the bilateral FPA, DLPFC, and r-MC but not in the other regions.

The current results support those of Lucas et al. (2012) and Schmit et al. (2015). They found that inhibitory control performance was improved during high-intensity exercise despite a decrease in cerebral oxygenation in the PFC. One of our previous studies (Huang et al., 2019) also found that self-paced low-intensity cycling resulted in lower in-task oxy-Hb concentrations in the FPA and DLPFC. Conversely, the present findings are in contrast with a previous study by Stone et al. (2020), which examined cognitive flexibility during graded exercise in military personnel. They found that PFC oxygenation significantly rose across exercise intensities. Similarly, Tempest and Reiss (2019) measured working memory performance using the n-back task under different exercise intensities. They found significant activation in the left PFC while cycling at moderate intensity. Therefore, the cortical hemodynamic changes while simultaneously performing cognitive and motor tasks remain to be elucidated in future studies.

The current study was among the first few ones to examine the in-task cortical activity during aerobic exercise by fNIRS. This study also has some limitations. First, due to the limitation of fNIRS measurement, the set-up of source and detector probes primarily covered the PFC and part of the pre-motor region. The cortical activity in parietal regions and primary motor cortex was not monitored during the task. Therefore, the relationship and interaction of cortical activity between the PFC and other brain regions were not examined. Second, the current study's duration of simultaneously performing cognitive tasks and cycling was about 8 minutes. Potential dynamic changes in working memory and cortical activity during prolonged exercise need investigation in future studies. Third, the study was conducted on young adults; therefore, the findings cannot be directly generalized to other age groups. Future studies are needed to verify the findings in broader age groups.

Conclusions

The findings suggested that the concurrent performance of working memory was improved during acute aerobic exercise, as indicated by faster RT. However, in-task cortical activity was decreased in bilateral FPA, DLPFC, and r-MC.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving human participants were reviewed and approved by Institutional Review Board for Human Research Protections, Shanghai Jiao Tong University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

KZ and TH: conceptualization and writing—original draft preparation. KZ, YC, TH, and ZD: methodology. KZ and ZD: formal analysis. KZ, YC, and ZD: resources. KZ, ZD, JQ, YC, SL, and TH: data collection and writing—review and editing. KZ, SL, and TH: data curation. TH: supervision and project administration. All authors have read and approved to the submitted version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnbeh.2022.884490/full#supplementary-material

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TYPE Review
PUBLISHED 23 September 2022
DOI 10.3389/fnbeh.2022.957677

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SPECIALTY SECTION
This article was submitted to Motivation and Reward, a section of the journal Frontiers in Behavioral Neuroscience

RECEIVED 31 May 2022
ACCEPTED 29 August 2022
PUBLISHED 23 September 2022

CITATION
Sudo M, Costello JT, McMorris T and Ando S (2022) The effects of acute high-intensity aerobic exercise on cognitive performance: A structured narrative review.
Front. Behav. Neurosci. 16:957677.
doi: 10.3389/fnbeh.2022.957677

The effects of acute high-intensity aerobic exercise on cognitive performance: A structured narrative review

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It is well established that acute moderate-intensity exercise improves cognitive performance. However, the effects of acute high-intensity aerobic exercise on cognitive performance have not been well characterized. In this review, we summarize the literature investigating the exercise-cognition interaction, especially focusing on high-intensity aerobic exercise. We discuss methodological and physiological factors that potentially mediate cognitive performance in response to high-intensity exercise. We propose that the effects of high-intensity exercise on cognitive performance are primarily affected by the timing of cognitive task (during vs. after exercise, and the time delay after exercise). In particular, cognitive performance is more likely to be impaired during high-intensity exercise when both cognitive and physiological demands are high and completed simultaneously (i.e., the dual-task paradigm). The effects may also be affected by the type of cognitive task, physical fitness, exercise mode/duration, and age. Second, we suggest that interactions between changes in regional cerebral blood flow (CBF), cerebral oxygenation, cerebral metabolism, neuromodulation by neurotransmitters/neurotrophic factors, and a variety of psychological factors are promising candidates that determine cognitive performance in response to acute high-intensity exercise. The present review has implications for recreational, sporting, and occupational activities where high cognitive and physiological demands are required to be completed concurrently.

KEYWORDS
cognition, dual task, cerebral blood flow, cerebral oxygenation, cerebral metabolism, neuromodulation

Introduction

A growing body of evidence suggests that acute moderate-intensity exercise improves cognitive performance (Lambourne and Tomporowski, 2010; Chang et al., 2012; Ando et al., 2020; McMorris, 2021). It has been speculated that the relationship between exercise intensity and cognitive performance is inverted-U shaped (Lambourne and Tomporowski, 2010; Chang et al., 2012; McMorris, 2021). In the inverted-U theory, acute exercise gradually increases arousal to an optimal level from rest to moderate intensity and thus improves cognitive performance. A recent review summarized that improvements in cognitive performance following moderate-intensity exercise are frequently accompanied by the changes in brain activation assessed by electroencephalogram (EEG) (Kao et al., 2020), which appears to support the theory that acute exercise alters brain activity and that this is associated with cognitive performance. Acute high-intensity aerobic exercise leads to metabolic, circulatory, and neurohormonal changes at the level of the brain (Ide and Secher, 2000; Meeusen et al., 2001; Nybo and Secher, 2004; Ogoh and Ainslie, 2009; Seifert and Secher, 2011). In contrast to moderate-intensity exercise, theoretically, high-intensity exercise may, therefore, also lead to altered, and potentially impaired cognitive performance. Indeed, the inverted-U theory predicts that high-intensity exercise increases arousal levels beyond the optimal level and leads to a temporary reduction in cognitive performance. However, the current literature base detailing the effects of high-intensity exercise on cognitive performance is not fully supportive of this theory and is somewhat ambiguous and contradictory (Browne et al., 2017; Moreau and Chou, 2019; Cantelon and Giles, 2021; McMorris, 2021; Zheng et al., 2021).

Dietrich and Audiffren (2011) proposed the hypofrontality hypothesis to explain how acute high-intensity exercise affects cognitive performance. The prefrontal cortex (PFC) orchestrates higher-order brain function including cognitive function (Miller and Cohen, 2001; Cools and Arnsten, 2021) and is thought to play a central role in cognitive performance. Acute exercise activates brain regions including motor and sensory cortices, insular cortex, and cerebellum (Williamson et al., 1997; Christensen et al., 2000; Hiura et al., 2014). Hence, the hypofrontality theory speculates that extensive activation of motor and sensory systems during high-intensity exercise likely attenuates higher-order functions of the PFC as the brain has finite metabolic resources (Dietrich and Audiffren, 2011). More recently, McMorris proposed an interoceptive model to explain the effects of high-intensity exercise on cognitive performance (McMorris, 2021). This model offers a more holistic overview of the interaction as it incorporates motivation, perceived effort costs, and perceived availability of resources, together with regional activations and neurotransmitter releases in the brain. Nevertheless, to date, the physiological and psychological mechanism(s) mediating the effects of acute high-intensity exercise on cognitive performance are poorly understood.

In this review, we first summarize the findings of studies investigating the exercise-cognition interaction, especially focusing on high-intensity aerobic exercise. Then, we explore methodological and physiological factors which may alter cognitive performance in response to high-intensity exercise. This review has implications for recreational, sporting, and occupational activities where high cognitive and physiological demands are simultaneously required.

Methodology

A literature search was undertaken using Pubmed to identify studies that examined the effects of high-intensity aerobic exercise on cognitive performance, assessed during and/or after exercise. The reference lists of relevant articles were also searched. The searches were undertaken in February 2022 and relevant articles were obtained. This review focused on healthy adults, and no restrictions were placed on publication date, study design, methodology, or method of assessing cognitive performance. High-intensity aerobic exercise was defined as exercise equating to $\geq$ 80% maximum power output (Browne et al., 2017), $\geq$ 80% maximal oxygen uptake ($\dot{V}O_2$) (McMorris, 2016b), or equivalent [e.g., $\geq$ 80% maximal heart rate (HR)]. Physiological demands are different between continuous and intermittent high-intensity exercise. Thus, we included high-intensity aerobic exercise in this review, and studies incorporating high-intensity interval exercise (HIIE) were considered outside the scope of this review. If specifically interested in this, readers are referred to a recent review that has already explored the effects of HIIE on executive function (Hsieh et al., 2021). In addition, we did not include studies conducted in extreme environments, such as hypoxia and hot/cold environments. However, we referred to evidence from HIIE studies, or studies in extreme environments, for discussion since physiological mechanisms underlying cognitive improvement/impairment in response to HIIE exercise or exercise in extreme environments are, at least partly, shared with those induced by high-intensity aerobic exercise.

Results

Details of the included studies are shown in **Table 1**, comprising a total of 40 studies (assessed during exercise only, n = 20; assessed both during and after exercise, n = 3; assessed after exercise only, n = 17). In many studies, cognitive performance was impaired during high-intensity exercise (Chmura et al., 1994; McMorris and Keen, 1994; Brisswalter et al., 1997; McMorris et al., 2009; Labelle et al., 2013; Wang et al., 2013; Dutke et al., 2014; Mekari et al., 2015;

TABLE 1 Summary of the findings.

References	Participants (F)	Category of cognitive task	Cognitive task(s) (number of trials, duration)	Exercise modality/intensity	Exercise duration (high intensity only) or until exhaustion	Timing of cognitive task	Physiological variables	Main findings
Chmura et al. (1994)	N = 22 (0) Young	Psychomotor task	Choice RT (30 trials, 107 s)	Cycling Near maximal (300 W)	6 min	During	Blood catecholamine, lactate	RT: impairment
McMorris and Keen (1994)	N = 12 (4) Young	Psychomotor task	Simple RT (15 trials)	Cycling 100% maximum workload	Not reported	During	-	RT: impairment
McMorris and Graydon (1997)	N = 12 (0) Young	Attentional task executive function	Soccer specific visual search task (30 slides) Soccer specific decision making task (15 trials)	Cycling 100% maximum power output	Not reported	During	-	Visual search: improvement Decision making: improvement
McMorris et al. (2009)	N = 24 (0) Young	Executive function	Flanker task (96 trials)	Cycling 80% maximum aerobic power	15 min or until exhaustion	During	Blood catecholamine, adrenocorticotropic hormone, cortisol	RT: impairment Accuracy: impairment
Ando et al. (2011)	N = 12 (0) Young	Executive function	Flanker task (40 trials, 3 min 20 s)	Cycling 80% $\dot{V}O_{2peak}$	6.5 min	During	Cerebral oxygenation	EMG-RT≈ Accuracy≈
Huertas et al. (2011)	N = 18 (0) Young	Executive function	Attention network test (modified flanker task, 480 trials, 25 min)	Cycling 95% LT	25 min	During	Blood lactate	RT: improvement
Shields et al. (2011)	N = 30 (15) Young	Attentional task	Visual threat-detection task (256 trials)	Cycling 80% maximal HR	Not reported	During	-	RT: improvement Accuracy: improvement
Labelle et al. (2013)	N = 37 (18) Young High fit = 16 Low fit = 21	Executive function	Stroop task (80 trials)	Cycling 80% peak power output	6.5 min	During	-	Accuracy: impairment RT variability: impairment in lower fit
Wang et al. (2013)	N = 80 (31) Young	Executive function	Wisconsin card sorting test (128 response cards)	Cycling 80% HRR	30 min	During	-	Performance: impairment
Dutke et al. (2014)	N = 60 (14) Young	Memory task attentional task (simultaneously)	Word comparison (Primary task, 60 trials, 27 min) Interval production (Secondary task, press a button every 2 s, 27 min)	Cycling 120% AT	> 27 min	During	-	Number of correct response≈ Response time≈ Interval production error: impairment
Davranche et al. (2015)	N = 14 (3) Young	Executive function	Simon task (200 trials, 4 min)	Cycling 20% above VT	20 min	During	-	RT: improvement Accuracy≈
Mekari et al. (2015)	N = 19 (12) Young	Executive function	Stoop task (30 trials × 2 blocks)	Cycling 85% peak power output	9 min	During	Cerebral oxygenation	RT: impairment Accuracy: impairment
Schmit et al. (2015)	N = 15 (5) Young	Executive function	Flanker task (40 trials, as many blocks as possible)	Cycling 85% maximal aerobic power	Until exhaustion	During	Cerebral oxygenation	RT≈ Accuracy: impairment
Smith et al. (2016)	N = 15 (9) Young	Executive function	Go/No-Go task (100 trials, 2 min)	Running 90% HRR	10 min	During	-	RT: impairment Accuracy: impairment
Gonzalez-Fernandez et al. (2017)	N = 24 (12) Young	Psychomotor task	Psychomotor vigilance task (mean 46.8 trials)	Cycling 100% ventilatory anaerobic threshold	5 min	During	-	RT: impairment

(Continued)

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TABLE 1 (Continued)

References	Participants (F)	Category of cognitive task	Cognitive task(s) (number of trials, duration)	Exercise modality/intensity	Exercise duration (high intensity only) or until exhaustion	Timing of cognitive task	Physiological variables	Main findings
Tempest et al. (2017)	*N* = 14 (5) Young	Executive function	Flanker task (2 min × 10 blocks) 2-back task (60 trials × 10 blocks, 20 min)	Cycling 10% above VT	60 min	During	Cerebral oxygenation	RT (flanker task): improvement Accuracy (n-back): impairment
Ciria et al. (2019)	*N* = 20 (0) Young	Attentional task	Oddball task (20 min)	Cycling 80% $\dot{V}O_{2peak}$	20 min	During	EEG	RT≈ Accuracy≈
Tempest and Reiss (2019)	*N* = 13 (7) Young	Executive function	N-back task (0-back, 60 trials; 2-back, 60 trials)	Cycling 115% first ventilatory threshold (VT1)	16 min	During	Cerebral oxygenation (fNIRS)	Response time≈ Accuracy≈
Komiyama et al. (2020)	*N* = 17 (0) Young	Executive function	Spatial delayed response Go/No-Go tasks (24 trials, ∼5 min)	Cycling 80% $\dot{V}O_{2peak}$	8 min	During	Middle cerebral artery blood velocity Cerebral oxygenation	RT≈ Accuracy: impairment
Stone et al. (2020)	*N* = 13 (5) Young	Executive function	Cedar operator workload assessment tool	Running 100% HRR	Until exhaustion	During	Cerebral oxygenation	Accuracy: impairment
Travlos and Marisi (1995)	*N* = 20 (0) Young High fit = 10 Low fit = 10	Attentional task psychomotor task	Random number generation test Choice RT (15 trials × 4)	Cycling during 80% $\dot{V}O_{2max}$ and after volitional exhaustion	Until exhaustion (> 10 min)	During/ immediately after	-	Random number generation test (during)≈ RT (after)≈
Brisswalter et al. (1997)	*N* = 20 (0) Young High fit = 10 Low fit = 10	Psychomotor task	Simple detection RT (20 trials)	Cycling during 80% maximal aerobic power	10 min	During/1 min after	-	RT (during): impairment in only low fit Accuracy≈ in both groups
Fery et al. (1997)	*N* = 13 (0) Young	Memory task	Short-term memory task (20 trials)	Cycling during 90% $\dot{V}O_{2max}$ and Volitional exhaustion	Until exhaustion	During/ immediately after	-	RT (during)≈ RT (after): impairment
Kamijo et al. (2004a, 2004b)	*N* = 12 (0) Young	Executive function	S1-S2 RT (Go/No-Go) task (60 trials, 10 min)	Cycling Volitional exhaustion	Until exhaustion	Immediately after (< 3 min)	EEG (CNV, P300)	EMG-RT≈
McMorris et al. (2005)	*N* = 12 (0) Young	Psychomotor task	Whole body choice RT (9 trials)	Cycling 100% maximal power output	Until exhaustion	Immediately after (20 s later)	Blood lactate	RT: impairment
Winter et al. (2007)	*N* = 27 (0) Young	Memory task	Vocabulary learning task (600 training trials + retention)	Running (two sprints, started at 8 km/h, increased every 10 s by 2 km/h) Volitional exhaustion	Until exhaustion	15 min after	Blood catecholamine, BDNF	Learning speed: improvement RT: improvement (1 week later)
Coco et al. (2009)	*N* = 17 (0) Young	Psychomotor task Attentional task	RT task Attention and concentration task	Cycling Volitional exhaustion Lactate infusion (N = 6)	Until exhaustion	5 min after	Blood lactate	RT: impairment Accuracy: impairment
Luft et al. (2009)	*N* = 30 (7) Young	Psychomotor task Executive function Memory task Attentional task	Simple RT (35 correct trials, 90 s) Choice RT (30 correct trials, 90 s) Working memory task (one back task, 30 correct trials, 90 s) Short-term memory task (42 trials, 2–3 min) Continuous monitoring task (30 correct trials, 90 s)	Running Volitional exhaustion	Until exhaustion	10–15 min after	HR variability	Working memory: improvement Others≈

(Continued)

TABLE 1 (Continued)

References	Participants (F)	Category of cognitive task	Cognitive task(s) (number of trials, duration)	Exercise modality/intensity	Exercise duration (high intensity only) or until exhaustion	Timing of cognitive task	Physiological variables	Main findings
Thomson et al. (2009)	*N* = 163 (0) Young	Psychomotor task	Speed discrimination (decision-making)	Running Volitional exhaustion	Until exhaustion	1 min after	-	Time: improvement Accuracy: impairment
Griffin et al. (2011)	*N* = 47 (0) Young	Memory task Executive function	Face-name matching task Stroop task	Running Volitional exhaustion	Until exhaustion	< 30 min After	Blood BDNF, IGF-1	Face-name matching task: improvement Stroop task≈
Etnier et al. (2016)	*N* = 16 (7) Young	Memory task	Rey Auditory Verbal Learning Test (15 words × 2)	Running Volitional exhaustion	Until exhaustion	Immediately after (after blood sampling)	Blood BDNF	Memory performance: improvement (24 h later)
Hwang et al. (2016)	*N* = 58 (32) Young	Executive function	Stroop test (100 items × 3 conditions, 4 min) Trail making test (< 2 min)	Running Target HR corresponding to 85–90% $\dot{V}O_{2max}$	10 min	10 min after	Blood BDNF	Stroop test: improvement Trail making test: improvement
Chang et al. (2017)	*N* = 36 (36) Young	Executive function	Stroop test (neutral 60 s, incongruent 60 s)	Running 80% HRR	30 min	15 min after	Cerebral oxygenation	RT≈
Sudo et al. (2017)	*N* = 32 (0) Young	Executive function	Spatial delayed response task (20 trials) Go/No-Go task (20 trials)	Cycling Volitional exhaustion	Until exhaustion	2 min after	Cerebral oxygenation, Blood catecholamine, BDNF, IGF-1, lactate	RT≈ Accuracy≈
Zimmer et al. (2017)	*N* = 119 (41) Young	Executive function	Tower of London	Cycling Volitional exhaustion	Until exhaustion	Immediately after (< 3 min)	Blood lactate	Thinking time: impairment
Du Rietz et al. (2019)	*N* = 29 (0) Young	Executive function Psychomotor task	Cued continuous performance task (modified Go/No-Go task, 80 trials, 11 min) Flanker task (400 trials, 13 min) Choice RT task (72 trials, 10 min)	Cycling 20% delta (difference between gas exchange threshold and $\dot{V}O_{2peak}$)	20 min	30 min after	EEG	RT≈ Accuracy≈
Hill et al. (2019)	*N* = 13 (0) Young	Executive function	Flanker task (100 trials, < 3 min)	Cycling and arm cranking Volitional exhaustion	Until exhaustion	Immediately after	-	Cycling: impairment Arm cranking: improvement
Coco et al. (2020a)	*N* = 30 (?) Young = 15 Old = 15	Psychomotor task Executive function	Simple RT Stroop color word test (50 names, 50 circles, and 50 words) Trail making test	Cycling Volitional exhaustion	Until exhaustion	Immediately after	Blood lactate	Simple RT: impairment Stroop Color Word Test: impairment Trail Making Test: improvement (Young)
Loprinzi et al. (2021)	*N* = 120 (77) Young	Memory task	Word list memory task (15 words)	Running 75% HRR	20 min	5 min after	-	Memory: improvement
Marin Bosch et al. (2021)	*N* = 18 (0) Young	Psychomotor task Memory task	Psychomotor vigilance task (RT) Associative memory task (8 series of 6 successive pictures)	Cycling 75% maximal cardiac frequency	15 min	24 min after (Psychomotor task) and 69 min after (memory task)	Neural activity (fMRI), Blood endocannabinoids, BDNF	RT≈ Accuracy≈

F, females; N, number of participants; RT, reaction time; W, watts; $\dot{V}O_{2peak}$, peak oxygen uptake; EMG, electromyogram; LT, lactate threshold; HR, heart rate; HRR, heart rate reserve; AT, anaerobic threshold; VT, ventilatory threshold; EEG, electroencephalogram; fNIRS, functional near-infrared spectroscopy; CNV, contingent negative variation; P300, positive 300; $\dot{V}O_{2max}$, maximal oxygen uptake; BDNF, brain-derived neurotrophic factor; IGF-1, insulin-like growth hormone factor-1; fMRI, functional magnetic resonance imaging. ≈, no effect.

Schmit et al., 2015; Smith et al., 2016; Gonzalez-Fernandez et al., 2017; Tempest et al., 2017; Komiyama et al., 2020; Stone et al., 2020). In these studies, impairments in both reaction time (RT) and accuracy were frequently observed. Seven studies reported no changes in cognitive performance (Travlos and Marisi, 1995; Fery et al., 1997; Ando et al., 2011; Dutke et al., 2014; Ciria et al., 2019; Tempest and Reiss, 2019; Komiyama et al., 2020). Five studies reported improvement in RT and/or accuracy during high-intensity exercise (McMorris and Graydon, 1997; Huertas et al., 2011; Shields et al., 2011; Davranche et al., 2015; Tempest et al., 2017).

Conversely, cognitive performance after high-intensity exercise is heterogeneous; with improvements (Winter et al., 2007; Luft et al., 2009; Thomson et al., 2009; Griffin et al., 2011; Etnier et al., 2016; Hwang et al., 2016; Hill et al., 2019; Coco et al., 2020a; Loprinzi et al., 2021), impairments (Fery et al., 1997; McMorris et al., 2005; Coco et al., 2009, 2020a; Thomson et al., 2009; Zimmer et al., 2017; Hill et al., 2019), and no changes (Travlos and Marisi, 1995; Brisswalter et al., 1997; Kamijo et al., 2004a,b; Luft et al., 2009; Griffin et al., 2011; Chang et al., 2017; Sudo et al., 2017; Du Rietz et al., 2019; Marin Bosch et al., 2021) reported within the literature. These findings suggest that cognitive performance after high-intensity exercise appears to be dependent on experimental design (*see below*). In the following sections, we discuss the methodological, physiological, and psychological factors that affect cognitive performance "*during*" and "*after*" high-intensity exercise.

Methodological factors

Here we discuss the potential methodological and experimental factors that contribute to the inconsistent findings. These include the following: timing of cognitive task, type of cognitive task, physical fitness, exercise mode/duration, and age.

Timing of cognitive task

When participants perform cognitive tasks during exercise, they perform the exercise and cognitive tasks simultaneously (i.e., a dual-task paradigm). However, when cognitive tasks are performed after exercise, participants only perform a single task. A meta-analysis reported higher effect sizes in single-task conditions (after exercise) when compared with dual-task conditions (during exercise) (Lambourne and Tomporowski, 2010), while another meta-analysis reported that effect sizes were not different between single and dual-task conditions (Chang et al., 2012). Furthermore, McMorris and Hale (2012) undertook statistical analyses and found that there were no differences in effect sizes obtained during compared after exercise. Nevertheless, as recently highlighted (McMorris, 2021), the timing of the cognitive tasks is typically less considered within the literature.

Table 1 indicates that the adverse effects are most prominent *during* high-intensity exercise. These findings are corroborated by a recent review and suggest that impairments in cognitive performance are more likely to occur during high-intensity exercise (Zheng et al., 2021). Based on the assumption that metabolic resources are limited in the brain, extensive activation in several brain regions (e.g., motor and sensory cortices) may attenuate higher-order functions of the PFC and impair cognitive performance (Dietrich and Audiffren, 2011). Furthermore, in the majority of the included studies, cognitive performance was assessed using manual responses where activations of the motor-related areas are required. Given a limited capacity of the brain to simultaneously activate multiple regions involved in cognitive performance and high-intensity exercise, it is plausible that cognitive performance is more likely to be impaired during high-intensity exercise, particularly when both cognitive and physiological demands are high. Indeed, in four studies reporting cognitive improvement during high-intensity exercise (Huertas et al., 2011; Shields et al., 2011; Davranche et al., 2015; Tempest et al., 2017), exercise intensities were relatively less demanding (i.e., HR $<$ 170 bpm). Relatively lower physiological demands may be responsible for cognitive improvements during high-intensity exercise in these studies. Furthermore, McMorris (2021) argued that performance would depend to a large extent on the perception of task costs (demands) and resources available. These two judgments may be difficult to make in the dual-task situation, leading to over- or under-confidence. This could alter motivation, which would affect cognitive performance.

A recent meta-analysis demonstrated that acute high-intensity exercise had a small, significant facilitating effect on cognitive performance *after* high-intensity exercise (Moreau and Chou, 2019). In the current review, we observed that cognitive performance after high-intensity exercise is inconsistent: and improvements, impairments, and no changes were reported. EEG studies reported reductions in P3 amplitudes after high intensity (Kamijo et al., 2004b) or HIIE (Kao et al., 2017). On the contrary, Du Rietz and colleagues reported improvements in P3 amplitude and delta power reflecting executive and sustained attention after high-intensity exercise (Du Rietz et al., 2019). These findings suggest that brain activity after exercise may be dependent on the experimental design employed (e.g., exercise intensity, time delay after exercise). Indeed, most physiological changes start to recover immediately after high-intensity exercise (Ide et al., 2000; Gonzalez-Alonso et al., 2004; Curtelin et al., 2017; Sudo et al., 2017). Thus, rapid recovery of physiological variables to homeostatic resting levels may, at least in part, explain the contradictory findings related to cognitive performance after high-intensity exercise. To explore this possibility, we summarized the impacts of the timeframe in which cognitive

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performance was assessed after exercise (Table 2). When multiple cognitive tasks were examined in a single study, or when both improvement and impairment were reported in a cognitive task (e.g., improvement in RT and impairment in accuracy), all results are reported. We observed heterogeneous findings when cognitive performance was assessed within 5 min of completing high-intensity exercise. Intriguingly, however, no impairments were reported when the timing of cognitive tasks was > 6 min after exercise. These findings support the notion that a rapid recovery to homeostatic resting levels is critical for cognitive performance after high-intensity exercise. Taken collectively, we propose that the effects of high-intensity exercise on cognitive performance are closely related to, and impacted by, the timing of cognitive task (during vs. after exercise, and the time delay after exercise).

Type of cognitive task

Different brain regions are thought to be activated during different cognitive tasks (Macintosh et al., 2014; Chen A. G. et al., 2016; Won et al., 2019). Thus, we can assume that the type of cognitive task is one of the factors that determine how acute high-intensity exercise impacts cognitive performance. This may be particularly relevant when exercise and cognitive tasks are concurrently performed since multiple brain regions are presumably activated. In this review, we classified the type of cognitive task into executive function, psychomotor, memory, and attentional tasks (Table 3). Executive function encompasses several subdomains and consists of basic components of inhibition, working memory, and cognitive flexibility (Diamond, 2013). Thus, based on the included studies, we classified executive function into response inhibition (Go/No-Go task), interference control (Flanker task, Simon task, and Stroop task), working memory (n-back task and spatial delayed response task), and others (soccer-specific task, Wisconsin card sorting task, Cedar Operator Workload Assessment Tool, Tower of London, and Trail making test).

During high-intensity exercise, impairments in cognitive performance were prominent in executive function and psychomotor tasks (Table 3), which is thought to be closely related to dual-task paradigm. Thus, in most cognitive tasks, adverse effects are more likely to occur during high-intensity exercise. Conversely, we found improvements in several studies. In three studies (Huertas et al., 2011; Davranche et al., 2015; Tempest et al., 2017), cognitive improvements were observed in interference control (i.e., Flanker task and Simon task). These findings imply that performances in these cognitive tasks may benefit from high-intensity exercise relative to the other subcomponents of executive function. Furthermore, in the study reporting improvements in soccer-specific cognitive tasks (both soccer-specific and attentional tasks) in college soccer players (McMorris and Graydon, 1997), the cognitive tasks were probably autonomous to the soccer players and therefore less demanding. Hence, cognitive improvements during high-intensity exercise appear to be related to cognitive demands.

A meta-analysis review reported that facilitating effects of performance were similarly observed in subcomponents of executive function (i.e., working memory, inhibitory control, cognitive flexibility, and attention) after high-intensity exercise (Moreau and Chou, 2019). In the present review, we failed to find clear associations between the type of cognitive task and cognitive performance after high-intensity exercise. It should be noted, however, that improvements in memory

TABLE 2 Summary of impacts of time delay after exercise.

0–5 min			6–10 min			11–20 min			>20 min		
Improvement (↑)	No change (↔)	Impairment (↓)	↑	↔	↓	↑	↔	↓	↑	↔	↓
●●●●●	●●●●●	●●●●●●●●●	●●			●●	●●●●●		●	●●●●●●	

Number of black circles indicates the number of studies.

TABLE 3 Summary of impacts of the type of cognitive task.

	Executive function			Psychomotor task			Memory task			Attentional task		
	Improvement (↑)	No change (↔)	Impairment (↓)	↑	↔	↓	↑	↔	↓	↑	↔	↓
During	***●	†*#	†**$$##●●			●●●●		●●		●●	●●	●
After	*$#●●	†††*$$#	*$●	●	●●●●●●	●●●●	●●●●	●●	●		●	●

Number of symbols indicates the number of studies.
†Response inhibition (Go/No-Go task).
*Interference control (Flanker task, Simon task).
$Interference control (Stroop task).
#Working memory (n-back task, spatial delayed response task).
● Others (soccer-specific task, Wisconsin card sorting task, Cedar Operator Workload Assessment Tool, Tower of London, and Trail making test), psychomotor task, memory task, attentional task.

performance were often observed after high-intensity exercise (Winter et al., 2007; Griffin et al., 2011; Etnier et al., 2016; Loprinzi et al., 2021). In particular, high-intensity exercise may be beneficial for retention (Winter et al., 2007; Etnier et al., 2016; Loprinzi et al., 2021). Additional studies are necessary to further elucidate potential physiological mechanisms underlying the improvement. In this review, we may not have been sufficiently powered to identify the effects of different cognitive tasks/domains. Further research is required to establish the effects of high-intensity exercise on a variety of cognitive tasks and domains.

Physical fitness level of participants

It has been previously speculated that exercise-cognition interaction is influenced by physical fitness (Lambourne and Tomporowski, 2010; Chang et al., 2012). For example, despite matched relative exercise intensity, individuals with lower physical fitness levels were more susceptible to cognitive impairments during high-intensity exercise, when compared with those who had higher aerobic capacities (Brisswalter et al., 1997; Labelle et al., 2013). Furthermore, choice RT performance gradually improves during incremental exercise until at ~75% $\dot{V}O_{2max}$ in young soccer players (Chmura et al., 1994). Aerobic capacity has been suggested to be one of the moderators that affect cognitive performance in response to high-intensity exercise (Browne et al., 2017). McMorris (2021) claimed that fitness levels would affect the individual's perception of effort costs and, hence, their motivation level. Further, well-powered studies are also necessary to clarify the relationship between cognitive performance and physical fitness before this theory can be confirmed.

Exercise mode

A previous meta-analysis suggested that exercise mode is one of the factors that affect exercise-cognition interaction (Lambourne and Tomporowski, 2010). We summarized the impacts of high-intensity cycling and running in Table 4. The effects of high-intensity exercise on cognitive performance during cycling were inconsistent, but reductions in cognitive performance appeared to be more likely during cycling. Running is kinematically less stable compared to cycling, and thus it may be difficult to complete cognitive performance during high-intensity running. Indeed, only two studies examined cognitive performance during high-intensity running, and both reported impairments in cognitive performance (Smith et al., 2016; Stone et al., 2020). Given the nature of the dual-task paradigm, running may be more detrimental to cognitive performance relative to cycling during high-intensity exercise.

After high-intensity cycling, in most cases, we observed no changes or impairments in cognitive performance. Conversely, after high-intensity running, improvements or no changes in cognitive performance were predominant. Since participants perform only a cognitive task after exercise (i.e., single task) regardless of exercise mode, the findings are somewhat unexpected. There are several physiological differences in ventilatory and metabolic responses, HR, and motor unit recruitment between cycling and running (Millet et al., 2009). Hence, the recovery of physiological variables to resting levels could be different between high-intensity cycling and running. Collectively, these findings suggest that the mode of exercise is one of the factors that affect cognitive performance, and these effects are presumably influenced by the timing of cognitive task (during vs. after exercise, and the time delay after exercise). Future studies are required to understand how exercise mode influences cognitive performance after high-intensity exercise.

Exercise duration

Exercise duration also potentially affects cognitive performance in response to high-intensity exercise. We summarized the relationship between exercise duration and cognitive performance in Table 5. During exercise, cognitive impairments were observed when exercise duration was < 10 min. The findings were inconsistent when exercise duration was > 11 min or exhaustive exercise. Thus, it is less likely that exercise duration *per se* affects cognitive performance. Rather, interactions between exercise duration and intensity would be more important for cognitive performance during high-intensity exercise. In most studies that assessed cognitive performance after high-intensity exercise, exercise was continued until exhaustion

TABLE 4 Summary of impacts of exercise mode.

	Cycling (+ arm cranking)			Running		
	Improvement (↑)	No change (↔)	Impairment (↓)	↑	↔	↓
During	●●●●●●	●●●●●●●	●●●●●●●●●●●●			●●
After	●●	●●●●●●●●●●	●●●●●●●●	●●●●●●●●	●●●●	●

Number of black circles indicates the number of studies.

TABLE 5 Summary of impacts of exercise duration.

	<10 min			11–20 min			>20 min			Until exhaustion		
	Improvement (↑)	No change (↔)	Impairment (↓)	↑	↔	↓	↑	↔	↓	↑	↔	↓
During		●●	●●●●●●●	●	●●		●●	●	●●●		●●	●●●
After	●●	●		●	●●●●●			●		●●●●●●●	●●●●●●●●●	●●●●●●●●●

Number of black circles indicates the number of studies.

(**Table 5**). Nevertheless, the results were heterogeneous and suggest that exercise duration in isolation is not critical for cognitive performance after exhaustive exercise. Assuming that the duration of high-intensity exercise is likely limited, exercise duration alone is, therefore, not likely to determine cognitive performance.

Age

Coco and colleagues compared the effects of exhaustive exercise on the cognitive performance of young and older adults (Coco et al., 2020a). They reported impairments in the performance of simple RT and the Stroop color-word test after exhaustive exercise in both groups. However, improvements in trail making test were observed only in the younger group. These results suggest that the effects of high-intensity exercise on cognitive performance may be different in young and older adults. Cerebral perfusion appears to be lower in older individuals during high-intensity exercise, although the cerebral extraction of glucose, lactate, and oxygen is similar (Braz and Fisher, 2016). Thus, age may be one factor that may influence cognitive performance and reduced cerebral perfusion could affect cognitive performance in older individuals in particular. Given the brevity of studies in this area, definitive conclusion on the impact of age is not yet feasible.

Physiological factors

As noted above, high-intensity exercise induces a variety of physiological effects within the human brain. Here, we summarize and discuss the physiological factors that are linked to cognitive performance during and after high-intensity exercise and we identify some of the potential physiological factors that may contribute to the inconsistent findings. These include the separate and combined effects of cerebral blood flow (CBF), cerebral oxygenation, cerebral metabolism, neuromodulation by neurotransmitters and neurotrophic factors, and various psychological factors.

Cerebral blood flow

During exercise, CBF is regulated by complex interactions between neural activity and metabolism, partial pressure of oxygen, carbon dioxide (CO_2), blood pressure, cardiac output, and sympathetic nervous system activity (Ogoh and Ainslie, 2009; Smith and Ainslie, 2017). CBF gradually increases during mild- to moderate-intensity exercise in response to neural activity and metabolism (Ogoh and Ainslie, 2009). However, during high-intensity exercise, hyperventilation-induced hypocapnia constricts the cerebral vessels, thereby reducing CBF (Ogoh and Ainslie, 2009; Smith and Ainslie, 2017). This suggests that brain metabolic demands might be inadequate during high-intensity exercise. Ogoh et al. (2014) reported that an increase in CBF, achieved using CO_2 inhalation, did not affect cognitive performance during prolonged moderate-intensity exercise (Ogoh et al., 2014). More recently, Komiyama and colleagues tested the hypothesis that a reduction in CBF is directly linked to impairment in cognitive performance during high-intensity exercise (Komiyama et al., 2020). By restoring CBF *via* CO_2 inhalation, the authors demonstrated that middle cerebral artery (MCA) velocity (a surrogate for CBF) did not prevent impaired cognitive performance during high-intensity exercise. These results suggest that a reduction in CBF *per se* may not be responsible for impaired cognitive performance during high-intensity exercise. However, given that CBF supplies oxygen and nutrients, the association between cognitive performance and regional CBF (e.g., blood flow to the PFC) in response to high-intensity exercise should be further investigated. In particular, a recent study indicated physiological "uncoupling" between the PFC oxygenation and MCA velocity during high-intensity exercise with CO_2 inhalation (Hansen et al., 2020). Follow-up studies are needed to fully understand the association between regional CBF and cognitive performance in response to high-intensity exercise.

Cerebral oxygenation

Cerebral oxygenation reflects the balance between cerebral oxygen availability and utilization (Boushel et al., 2001;

Komiyama et al., 2017), which is generally measured from the PFC. Cerebral oxygenation reduces during high-intensity exercise close to maximal intensity (Rooks et al., 2010). Some studies suggest that a reduction in cerebral oxygenation is not associated with impairments in cognitive performance during high-intensity exercise (Ando et al., 2011; Schmit et al., 2015; Tempest et al., 2017). In contrast, others have indicated that impairments in cognitive performance were accompanied by reduction in cerebral oxygenation during high-intensity exercise (Mekari et al., 2015; Stone et al., 2020). The latter studies suggest that impairments in cognitive performance may be associated with attenuated PFC oxygenation. However, several studies have shown that cognitive performance improved during acute moderate-intensity exercise in hypoxia despite substantial reductions in cerebral oxygenation (Ando et al., 2013; Komiyama et al., 2015, 2017). Hence, it is likely that a reduction in cerebral oxygenation, in isolation, does not result in impaired cognitive performance. However, reduction in cerebral oxygenation during high-intensity exercise may impair cognitive performance in concert with other physiological factors.

Cerebral oxygenation starts to recover immediately after maximal exercise (Gonzalez-Alonso et al., 2004; Sudo et al., 2017). Notably, the degree of recovery of cerebral oxygenation following maximal exercise may be associated with cognitive performance (Sudo et al., 2017). This finding suggests that the recovery of cerebral oxygenation after high-intensity exercise may, at least in part, account for the differential effects of high-intensity exercise on cognitive performance between single (i.e., after) and dual (i.e., during) conditions.

Cerebral metabolism

It is generally accepted that blood glucose is the primary energy source for the brain at rest (Gold, 1995). Komiyama et al. (2016) reported that cognitive performance improves during moderate-intensity exercise after skipping breakfast. This suggests that substrates other than glucose may compensate for the reduced availability of blood glucose during moderate-intensity exercise. It is plausible that the same would be true for high-intensity exercise. Indeed, blood glucose uptake is thought to be reduced in the brain during high-intensity exercise (Kemppainen et al., 2005). In contrast, blood lactate substantially increases during/after high-intensity exercise, and it is taken up by the brain (Ide et al., 2000; Gonzalez-Alonso et al., 2004; Quistorff et al., 2008; Siebenmann et al., 2021). Several studies suggested that blood lactate

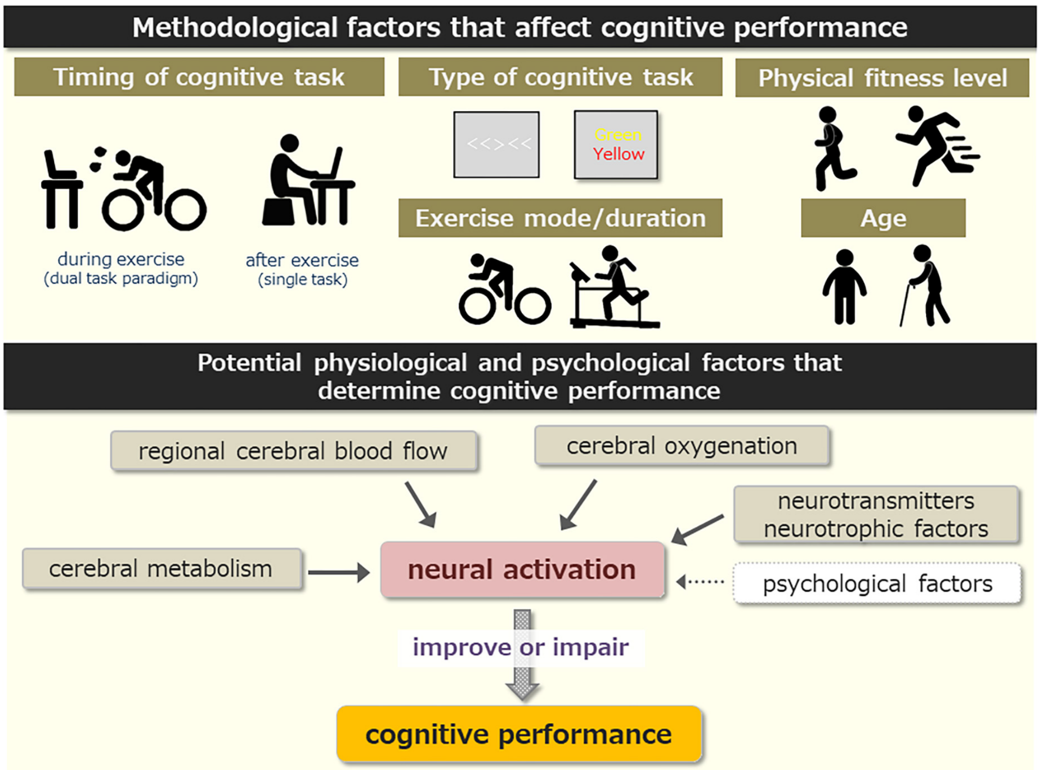

FIGURE 1
(Upper) Summary of methodological factors that affect cognitive performance in response to high-intensity exercise. (Lower) Potential physiological and psychological factors that mediate cognitive performance.

would provide energy that contributes to improvements in cognitive performance following HIIE (Tsukamoto et al., 2016; Hashimoto et al., 2018; Herold et al., 2022). In particular, Hashimoto et al. (2018) directly measured lactate uptake in the brain after HIIE and suggested that lactate production in extra-cerebral tissues supports brain function. On the contrary, Coco et al. (2020b) suggested that high levels of blood lactate have detrimental effects on cognitive performance. Interestingly, Coco et al. (2009) indicated that intravenous lactate infusion of a lactate solution impaired attentional performance. Hence, further studies are warranted to investigate how blood lactate acts as a mediator of exercise-induced alterations in cognitive performance (Ando et al., 2022).

Neuromodulation by neurotransmitters and neurotrophic factors

In humans, it is less clear how acute exercise alters central neurotransmitter release due to technical and methodological challenges. Nevertheless, given that rodent studies indicate that acute exercise releases neurotransmitters in the brain (Meeusen et al., 2001; Hasegawa et al., 2011; Goekint et al., 2012; Chen C. et al., 2016), acute exercise is likely to influence brain circuits involving a number of neurotransmitters including dopamine and noradrenaline (McMorris, 2016a; Ando et al., 2020). Dopamine and noradrenaline modulate the strength of the PFC network connections, and regulation of dopamine and noradrenaline is required for appropriate prefrontal cognitive function (Arnsten, 2011). Furthermore, excess noradrenaline and dopamine appear to weaken the signal-to-noise ratio, which may result in impairments in the PFC function (Arnsten, 2011; Cools and Arnsten, 2021). Hence, the available literature suggests that excess neuromodulators in the brain may have adverse effects on cognitive performance during/after high-intensity exercise. High-intensity exercise also seems to increase brain-derived neurotrophic factors (BDNFs) (Ferris et al., 2007; Winter et al., 2007; Fernandez-Rodriguez et al., 2021) and insulin-like growth hormone factor-1 (IGF-1) (Sudo et al., 2017). Several studies have implicated that changes in BDNF are associated with cognitive improvement induced by acute exercise (Winter et al., 2007; Lee et al., 2014; Skriver et al., 2014; Hwang et al., 2016). However, BDNF and IGF-1 are known to play a crucial role in angiogenesis, synaptogenesis, and neurogenesis following long-term exercise (Cotman and Berchtold, 2002; Voss et al., 2011; Nieto-Estevez et al., 2016). High concentrations of dopamine, noradrenaline, and BDNF are necessary for long-term potentiation, which is essential for long-term memory (McMorris, 2021). A couple of studies have shown positive effects of high-intensity exercise on long-term memory (Winter et al., 2007; Griffin et al., 2011). At present, it is premature to conclude that changes in BDNF and IGF-1 play a role in cognitive performance during/after high-intensity exercise.

Psychological factors

In most studies, psychological factors are typically not well considered when attempting to elucidate the effects of high intensity on cognitive performance. However, as suggested by McMorris (2021), psychological factors such as the motivation and perception of effort may affect the acute exercise–catecholamine–cognition interaction. Cantelon and Giles also suggested that psychological factors are moderating factors that affect exercise–cognition interaction (Cantelon and Giles, 2021). At present, and given the lack of empirical evidence, further investigations are needed to investigate the association between psychological factors and cognitive performance during and after high-intensity exercise.

Integration of physiological and psychological factors

It is likely that the effects of high-intensity exercise on cognitive performance are multifactorial and determined by the integration of several physiological and psychological factors (**Figure 1**). We propose that interactions of these factors influence neural activity associated with cognitive performance and that this determines cognitive performance during and after high-intensity exercise. This is consistent with McMorris (2021) claiming that the perception of physiological stress affects the motivation and perception of effort costs. However, the current literature base is insufficient to substantiate this speculation and this should be the focus of future research in this area. A recent fNIRS study detected cognitive task-related hemodynamic changes from the left PFC during high-intensity exercise (Tempest and Reiss, 2019). Furthermore, an fMRI study indicated that HIIE decreased brain activation associated with cognitive performance (Mehren et al., 2019). Thus, future studies using sophisticated neuroimaging methods (e.g., fNIRS, fMRI, and PET) are required to fully understand how a single bout of high-intensity exercise affects cognitive performance.

Conclusion

This narrative review summarized the literature examining the effects of acute high-intensity exercise on cognitive performance. We propose that the effects of high-intensity exercise on cognitive performance are primarily affected by a variety of methodological, physiological, and psychological factors. Specifically, these include the timing of cognitive task (during vs. after exercise, and the time delay after exercise), cognitive task(s), fitness level, exercise mode/duration, and age. It is also likely that a complex interaction between changes in regional CBF, cerebral oxygenation, cerebral metabolism, neurotransmitters/neurotrophic factors, and a variety of psychological factors contributes to the heterogeneous findings reported. The review is likely to have implications for recreational, sporting, and occupational activities where high cognitive and physiological demands are required simultaneously.

Author contributions

MS, JC, TM, and SA drafted the manuscript. All authors approved the final version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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