frontiers | Research Topics

Physical activity: a promising modifiable behavior to protect brain, cognition, and mental health across the lifespan

Edited by
María Rodriguez-Ayllon, Yaira Barranco-Ruiz and Jose Mora-Gonzalez

Coordinated by
Darío Bellón

Published in
Frontiers in Psychology
Frontiers in Human Neuroscience
Frontiers in Sports and Active Living

ISSN 1664-8714
ISBN 978-2-8325-6613-8
DOI 10.3389/978-2-8325-6613-8

Generative AI statement
Any alternative text (Alt text) provided alongside figures in the articles in this ebook has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

Physical activity: a promising modifiable behavior to protect brain, cognition, and mental health across the lifespan

Topic editors
María Rodriguez-Ayllon — Erasmus Medical Center, Netherlands
Yaira Barranco-Ruiz — University of Granada, Spain
Jose Mora-Gonzalez — University of Granada, Spain

Topic coordinator
Darío Bellón — University of Granada, Spain

Citation
Rodriguez-Ayllon, M., Barranco-Ruiz, Y., Mora-Gonzalez, J., Bellón, D., eds. (2025).
Physical activity: a promising modifiable behavior to protect brain, cognition, and mental health across the lifespan. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-6613-8

Table of contents

TYPE Editorial
PUBLISHED 02 July 2025
DOI 10.3389/fpsyg.2025.1636754

OPEN ACCESS

EDITED AND REVIEWED BY
Guy Cheron,
Université Libre de Bruxelles, Belgium

*CORRESPONDENCE
María Rodriguez-Ayllon
✉ maria.rodriguezay@gmail.com

†These authors have contributed equally to this work

RECEIVED 28 May 2025
ACCEPTED 13 June 2025
PUBLISHED 02 July 2025

CITATION
Mora-Gonzalez J, Barranco-Ruiz Y, Bellón D and Rodriguez-Ayllon M (2025) Editorial: Physical activity: a promising modifiable behavior to protect brain, cognition, and mental health across the lifespan. *Front. Psychol.* 16:1636754. doi: 10.3389/fpsyg.2025.1636754

Editorial: Physical activity: a promising modifiable behavior to protect brain, cognition, and mental health across the lifespan

Jose Mora-Gonzalez[1†], Yaira Barranco-Ruiz[1†], Darío Bellón[1] and María Rodriguez-Ayllon[2,3,4*]

[1]Department of Physical Education and Sports, Faculty of Sport Sciences, Sport and Health University Research Institute (iMUDS), University of Granada, Granada, Spain, [2]Biomedical Research Institute of Málaga and Nanomedicine Platform (IBIMA Plataforma BIONAND), Málaga, Spain, [3]Prevention and Health Promotion Research Network (redIAPP) and Chronicity, Primary Care and Health Promotion Research Network (RICAPPS), Instituto de Salud Carlos III (ISCIII), Madrid, Spain, [4]Department of Epidemiology, Erasmus University Medical Center, Rotterdam, Netherlands

KEYWORDS

exercise, mental health, sleep, healthy habits, brain health, cognition, prevention

Editorial on the Research Topic
Physical activity: a promising modifiable behavior to protect brain, cognition, and mental health across the lifespan

1 Introduction

Physical activity is increasingly recognized as a pivotal modifiable behavior with significant impacts on physical health, brain function, cognition, and mental wellbeing throughout life (Katzmarzyk et al., 2022; Domingos et al., 2021; Zhang et al., 2023; Erickson et al., 2019). Despite overwhelming evidence supporting its positive effects, global physical activity levels remain alarmingly low, presenting a significant public health challenge (Strain et al., 2024; World Health Organization, 2024; Guthold et al., 2020; Bull et al., 2020). This Research Topic highlights the powerful role of physical activity in promoting brain health and mental wellbeing, focusing on cognitive function, emotional regulation, and psychological distress across diverse populations and life stages. It also provides insights into some mechanisms linking physical activity with brain health outcomes.

2 Overview of contributions

2.1 Physical activity's role in youth: cognition, mental health, and development

Cui et al. explored the relationship between physical activity and cognitive abilities in Chinese adolescents. Their findings suggested that higher levels of physical activity are linked to better cognitive performance, especially in adolescents who initially showed lower cognitive abilities. The study also highlighted self-education expectations and learning behaviors as potential mechanisms linking physical activity with cognitive performance.

Building on this, Yan et al. examined how physical activity relates to mental health in middle school students from China. Their study emphasized that physical activity can enhance psychological wellbeing by reducing negative emotions and boosting self-efficacy. These two variables appear to be important pathways through which physical activity supports overall mental health during adolescence.

Zhang et al. conducted a systematic review and meta-analysis of 13 studies to examine brain activation patterns in children and adolescents engaged in physical activity. The analysis revealed consistent activation in frontal associative brain regions, such as the medial, middle, and inferior frontal gyri. Notably, exercises with greater variety elicited more activation in these areas, emphasizing the importance of incorporating diverse activities into intervention practices. The findings suggest that promoting variability in physical activities can optimize brain function in young individuals.

Complementing these studies, Xiang et al. explored how physical activity is related to academic achievement in Chinese secondary school students. They identified three pathways linking physical activity to better academic outcomes: social support, learning engagement, and a combination of both, where physical activity boosts social support, enhancing learning engagement and academic success. These findings suggest that physical activity can benefit students academically by fostering stronger social connections and greater engagement in learning.

2.2 Physical activity, self-perception, and mental health in college students

Jankauskiene and Baceviciene's study examined how mindfulness during physical activity relates to body appreciation among Lithuanian college students, considering the roles of sex and BMI. They found that mindfulness is linked to greater body appreciation, especially in individuals with higher BMI, highlighting the importance of integrating practices like present-moment awareness and body acceptance into physical activity.

Ke et al. studied the connection between physical activity and smartphone addiction in Chinese college students, showing that self-esteem mediates this relationship. Overall, regular physical activity was associated with lower smartphone dependency, suggesting that improving self-esteem through exercise could help manage technology-related behaviors.

Gutiérrez-Capote et al. explored the acute effects of physical activity on cognitive performance through basketball drills among Spanish college students. Their findings showed that even short bouts of physical activity can enhance cognitive function, suggesting benefits for educational settings where brief activity breaks may improve focus and learning.

2.3 Physical activity, depression, cognition, and trauma recovery in adults

Ibáñez et al. studied the relationship between physical activity, sedentary behavior, and depressive symptoms in Spanish adults with major depressive disorder (MDD) during different stages of the COVID-19 pandemic. They found that more sedentary time correlated with higher depressive symptoms, while light physical activity was linked to lower symptoms, except during strict lockdowns. This underscores the importance of reducing sedentary behavior and encouraging physical activity to manage depression, particularly during public health fluctuations.

Sewell et al. studied whether sleep mediates the effects of exercise on cognition in older adults in Australia. Acute high-intensity exercise showed no immediate effect on cognition or sleep, nor did sleep mediate this relationship. However, changes in light and deep sleep from baseline to post-intervention were linked to improvements in episodic memory at ∼24 h, regardless of the intervention. These findings suggest that while exercise did not directly affect cognition or sleep, sleep quality may independently enhance cognitive performance, highlighting the need for further research into the relationship between sleep, exercise, and cognition in this specific population.

Lastly, SantaBarbara et al. explored the associations of exercise with post-traumatic stress disorder (PTSD) symptoms, distress, pain, and sleep in trauma-exposed adults. Overall, participants meeting exercise guidelines reported reduced PTSD symptoms, lower distress and pain, and better sleep quality. The findings support exercise as a valuable therapeutic tool for improving mental health and resilience in trauma survivors.

3 Insights and future directions, and general conclusions

The studies in this Research Topic highlight the benefits of physical activity for brain, cognitive function, emotional regulation, and mental health across the lifespan. However, several areas warrant further exploration. Future research should focus on personalized physical activity interventions that consider individual preferences and characteristics, such as age, gender, and health status. For protecting mental health, physical activity types should align with personal preferences—whether team sports, yoga, or mindful movement practices—rather than focusing solely on aesthetic and general benefits. Promoting self-awareness during physical activity, such as mindfulness or body awareness, could further enhance engagement and adherence.

Notably, exercises with greater variety elicited more activation in key brain areas, emphasizing the importance of incorporating diverse activities into intervention practices. Promoting variability in physical activities can optimize brain function in young individuals. On the other hand, when used mindfully, smartphones can promote physical activity and support healthy lifestyle changes among youth, such as increasing physical activity. Instead of demonizing technology as a driver of sedentary behavior, efforts should focus on encouraging its responsible use. Enhancing digital literacy is key to helping young people harness technology's benefits while maintaining a balanced lifestyle.

Moreover, more long-term randomized controlled trials are needed to confirm the findings presented in this Research Topic, which primarily includes observational and short-term intervention studies. Finally, environmental factors, such as social contexts and external restrictions—like pandemic-related lockdowns, access to exercise facilities, or cultural barriers—can significantly impact the effectiveness of exercise interventions. Future research should consider these variables to ensure broad participation and maximize the benefits.

Author contributions

JM-G: Writing – review & editing, Writing – original draft. YB-R: Writing – original draft, Writing – review & editing. DB: Writing – original draft, Writing – review & editing. MR-A: Writing – review & editing, Writing – original draft, Conceptualization, Investigation, Supervision.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. María Rodriguez-Ayllon was supported by the Sara Borrell postdoctoral fellowship [CD23/00096- Instituto de Salud Carlos III (ISCIII)].

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.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Bull, F. C., Al-Ansari, S. S., Biddle, S., Borodulin, K., Buman, M. P., Cardon, G., et al. (2020). World health organization 2020 guidelines on physical activity and sedentary behaviour. *Br. J. Sports Med.* 54, 1451–1462. doi: 10.1136/bjsports-2020-102955

Domingos, C., Pêgo, J. M., and Santos, N. C. (2021). Effects of physical activity on brain function and structure in older adults: a systematic review. *Behav. Brain Res.* 402:113061. doi: 10.1016/j.bbr.2020.113061

Erickson, K. I., Hillman, C., Stillman, C. M., Ballard, R. M., Bloodgood, B., Conroy, D. E., et al. (2019). Physical activity, cognition, and brain outcomes: a review of the 2018 physical activity guidelines. *Med. Sci. Sports Exerc.* 51, 1242–1251. doi: 10.1249/MSS.0000000000001936

Guthold, R., Stevens, G. A., Riley, L. M., and Bull, F. C. (2020). Global trends in insufficient physical activity among adolescents: a pooled analysis of 298 population-based surveys with 1·6 million participants. *Lancet Child Adolesc. Health* 4, 23–35. doi: 10.1016/S2352-4642(19)30323-2

Katzmarzyk, P. T., Friedenreich, C., Shiroma, E. J., and Lee, I. M. (2022). Physical inactivity and non-communicable disease burden in low-income, middle-income and high-income countries. *Br. J. Sports Med.* 56, 101–116. doi: 10.1136/bjsports-2020-103640

Strain, T., Flaxman, S., Guthold, R., Semenova, E., Cowan, M., Riley, L. M., et al. (2024). National, regional, and global trends in insufficient physical activity among adults from 2000 to 2022: a pooled analysis of 507 population-based surveys with 5·7 million participants. *Lancet Glob. Health* 12, e1232–e1243. doi: 10.1016/S2214-109X(24)00150-5

World Health Organization (2024). Global levels of physical inactivity in adults: off track for 2030. Available online at: https://iris.who.int/handle/10665/378026 (accessed March 11, 2025).

Zhang, M., Jia, J., Yang, Y., Zhang, L., and Wang, X. (2023). Effects of exercise interventions on cognitive functions in healthy populations: a systematic review and meta-analysis. *Ageing Res. Rev.* 92:102116. doi: 10.1016/j.arr.2023.102116

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 05 October 2023
DOI 10.3389/fpsyg.2023.1207199

OPEN ACCESS

EDITED BY
Jose Mora-Gonzalez,
University of Granada, Spain

REVIEWED BY
Flávia Machado,
University of Porto, Portugal
Sebastián Del Rosso,
CONICET Centre for Research in Clinical Biochemistry and Immunology (CIBICI), Argentina
Andréa Wieck,
Pontifical Catholic University of Rio Grande do Sul, Brazil

*CORRESPONDENCE
Kelsey R. Sewell
✉ kelsey.sewell@murdoch.edu.au

RECEIVED 17 April 2023
ACCEPTED 18 September 2023
PUBLISHED 05 October 2023

CITATION
Sewell KR, Smith NDW, Rainey-Smith SR, Peiffer J, Sohrabi HR, Erickson KI and Brown BM (2023) The effect of acute exercise on objectively measured sleep and cognition in older adults.
Front. Psychol. 14:1207199.
doi: 10.3389/fpsyg.2023.1207199

The effect of acute exercise on objectively measured sleep and cognition in older adults

Kelsey R. Sewell[1*], Nathan D. W. Smith[1], Stephanie R. Rainey-Smith[1,2,3,4], Jeremiah Peiffer[1], Hamid R. Sohrabi[1,2,3,5], Kirk I. Erickson[6,7,8] and Belinda M. Brown[1,2,3]

[1]Centre for Healthy Ageing, Health Futures Institute, Murdoch University, Murdoch, WA, Australia, [2]School of Medical and Health Sciences, Edith Cowan University, Joondalup, WA, Australia, [3]Australian Alzheimer's Research Foundation, Sarich Neuroscience Research Institute, Nedlands, WA, Australia, [4]School of Psychological Science, University of Western Australia, Perth, WA, Australia, [5]Department of Biomedical Sciences, Macquarie University, Sydney, NSW, Australia, [6]Department of Psychology, University of Pittsburgh, Pittsburgh, PA, United States, [7]PROFITH "PROmoting FITness and Health Through Physical Activity" Research Group, Department of Physical and Sports Education, Faculty of Sport Sciences, Sport and Health University Research Institute (iMUDS), University of Granada, Granada, Spain, [8]AdventHealth Research Institute, Orlando, FL, United States

Background: Exercise can improve cognition in aging, however it is unclear *how* exercise influences cognition, and sleep may partially explain this association. The current study aimed to investigate whether objectively measured sleep mediates the effect of an acute exercise intervention on cognition in older adults.

Methods: Participants were 30 cognitively unimpaired, physically active older adults (69.2 ± 4.3 years) with poor sleep (determined via self-report). After a triple baseline cognitive assessment to account for any natural fluctuation in cognitive performance, participants completed either a single bout of 20-minutes of high intensity exercise on a cycle ergometer, or a control condition, in a cross-over trial design. Cognition was measured immediately post-intervention and the following day, and sleep (total sleep time, sleep onset latency, sleep efficiency, % of rapid eye movement sleep, light sleep and deep sleep) was characterized using WatchPAT™ at baseline (5 nights) and measured for one night after both exercise and control conditions.

Results: Results showed no effect of the exercise intervention on cognition immediately post-intervention, nor an effect of acute exercise on any sleep variable. There was no mediating effect of sleep on associations between exercise and cognition. However, a change from baseline to post-intervention in light sleep and deep sleep did predict change in episodic memory at the ~24 h post-intervention cognitive assessment, regardless of intervention condition.

Discussion: There was no effect of acute high intensity exercise on sleep or cognition in the current study. However, results suggest that associations between sleep and cognition may exist independently of exercise in our sample. Further research is required, and such studies may aid in informing the most effective lifestyle interventions for cognitive health.

KEYWORDS

exercise, cognition, sleep, older adults, high intensity

Introduction

There is a well-established link between habitual physical activity (bodily movement resulting in energy expenditure; Caspersen et al., 1985) and preservation of cognition in aging (Sofi et al., 2011; Blondell et al., 2014; Yoneda et al., 2021; Sewell et al., 2023a). However, evidence for the efficacy of exercise (i.e., structured/planned physical activity) interventions to improve cognitive function in older adults is inconsistent (Sink et al., 2015; Young et al., 2015). Lifestyle and genetic factors may affect individual cognitive response to exercise, contributing to inconsistencies in the literature (Erickson et al., 2022). It is increasingly important to understand factors that influence the exercise-cognition association in order to promote a precision approach to maintaining cognitive health in aging.

Sleep is one factor which may contribute to the strength of cognitive response to exercise interventions (Sewell et al., 2021). Poor sleep is associated with a greater risk of cognitive decline and dementia (Bubu et al., 2016), and increased slow wave activity during sleep may improve memory performance in older adults (Westerberg et al., 2015). Sleep stages may differentially influence aspects of cognitive function, for example rapid eye movement (REM) sleep is important for memory consolidation (Boyce et al., 2017). Exercise interventions can improve sleep outcomes, although this may be subject to specific sleep parameters (Kredlow et al., 2015). For example, acute exercise has been shown to benefit sleep duration, sleep onset latency (time taken to fall sleep), sleep efficiency (% of time in bed spent asleep), stage 1 sleep (light sleep) and slow wave sleep, specifically (Kredlow et al., 2015). Additional research is required to investigate these complex and specific associations between sleep characteristics, exercise and cognitive domains, in order to best preserve cognition in aging.

Few studies to date have investigated associations between sleep, exercise and cognition. However, some observational cross-sectional research indicates that physical activity may compensate for sleep-related cognitive deficits (Lambiase et al., 2014; Nakakubo et al., 2017; Sewell et al., 2023b). To the authors' knowledge, only one experimental study has examined the effect of an acute exercise intervention on sleep and cognition in cognitively unimpaired older adults (Won et al., 2019). Won et al. found that longer habitual sleep duration was associated with better executive function post-exercise, however, there was no relationship between exercise and executive function when sleep was not considered (Won et al., 2019). Based on these results, sleep duration may not only impact the strength of association between exercise and cognition, but also, sleep may partially explain this association; a paradigm which has been further investigated in observational studies.

Results from cross-sectional studies indicate self-reported and objectively measured sleep may partially explain the association between physical activity and cognition (Wilckens et al., 2018; Cheval et al., 2022). However, another observational study showed no mediating effect of self-reported sleep quality on the association between self-reported physical activity and global cognition (Yuan et al., 2020). Many variables may explain these disparate findings, specifically, self-reported vs. objectively measured sleep and physical activity, and differences in the parameter of focus for each variable (i.e., sleep efficiency vs. overall quality, physical activity frequency vs. total volume). Currently, there are no published experimental studies which examine the potential mediating effect of sleep on the exercise-cognition association, specifically measuring sleep staging (e.g., deep sleep, light sleep, REM sleep) and assessing multiple cognitive domains (e.g., attention, memory). Additionally, no study has examined these relationships with consideration of exercise intensity, which may influence exercise-induced sleep and cognitive change, specifically such that high-intensity exercise may produce the greatest benefit (Angevaren et al., 2007; Brown et al., 2012; Larsen et al., 2019; Oberste et al., 2019). Thus, additional exercise intervention studies utilizing objective sleep measures, and considering exercise intensity, are required to corroborate cross-sectional observational findings of a mediating role for sleep in the exercise-cognition relationship.

The current study was intended as a proof-of-concept trial to examine the effect of a high intensity acute exercise intervention on objectively measured sleep variables (total sleep time; TST, sleep efficiency, time spent in light sleep, deep sleep, and REM sleep), and cognition (executive function, memory and attention), in cognitively unimpaired older adults. In prior studies, exercise has been shown to acutely improve both sleep and cognition (Chang et al., 2014; Kredlow et al., 2015), thus an acute intervention was selected due to the novel, proof-of-concept nature of our study. Aim one was to determine whether our high intensity acute exercise intervention improved cognition immediately post-exercise, and aim two was to examine whether our high intensity acute exercise intervention improved sleep after exercise, compared to baseline. We hypothesized that both sleep and cognition would improve post-exercise. To corroborate observational studies discussed above, our third aim (the proof-of-concept aspect) was to determine whether any sleep variable mediated the association between acute high intensity exercise and performance on measures of memory, executive function or attention, the day following exercise. Based on Wilckens et al. (2018), we hypothesized that sleep efficiency would mediate associations between exercise and executive function. Additionally, based on associations with exercise (Kredlow et al., 2015) and memory (Westerberg et al., 2015), we hypothesized that time spent in deep sleep would mediate associations between exercise and memory.

Method

Participants

Participants for this study were 30 community-dwelling older adults aged 60–80 years who were physically "active," cognitively unimpaired, and self-reported poor sleepers. Participants were included if they reported meeting physical activity guidelines of ≥150 min of moderate intensity exercise per week within the last month (Haskell et al., 2007), but not regularly engaging in high intensity exercise. We recruited physically active participants to limit any risks associated with delivering a high intensity exercise intervention to sedentary individuals. Cognitive status was determined by score on the teleMoCA (telephone Montreal Cognitive Assesment, participants must score ≥17; Pendlebury et al., 2013), which was confirmed using the full version of the MoCA in the second cognitive session [inclusion based on Rossetti et al. (2011) norms]. Poor sleep was defined by scoring >5 on the Pittsburgh Sleep Quality Index (PSQI; Backhaus et al., 2002). Eligibility was determined using a semi-structured telephone interview which included collection of medical and demographic information pertaining to exclusion criteria, physical activity level assessment, completion of the teleMoCA and completion of the PSQI electronically. Exclusion criteria included: inability to undertake cycling-based exercise; inability to obtain medical clearance to participate in exercise; current or past history of major psychiatric conditions (e.g., schizophrenia, schizoaffective disorder, or bipolar disorder); untreated sleep apnoea (determined via self-report); shift work; recent travel through more than one time zone; excessive regular alcohol use; or an unstable medical condition (including uncontrolled diabetes mellitus or hypertension). If sleep apnoea symptoms were indicated via WatchPAT™ results, a report containing the results was sent to participants' general practitioner and recommended further testing, but participants were allowed to remain in the study. Prior to any exercise, participants completed the Exercise and Sports Science Australia adult pre-exercise screening questionnaire. Prior to participation in any procedures, written informed consent was obtained. The study was approved by the Human Research Ethics Committee of Murdoch University, Australia (2020/207), and was retrospectively registered as a clinical trial with the Australian New Zealand Clinical Trials Registry (ACTRN12621001514897).

Design and procedure

A triple-baseline cognitive assessment, including Cogstate (described later) at all three occasions and MoCA only at baseline two, was completed followed by a two-period (AB, BA) crossover design, performed in a counterbalanced order (Figure 1). The triple baseline cognitive assessment was utilized to understand variability due to measurement error, based on previous repeatability recommendations of the Cogstate Brief Battery (Falleti et al., 2006), and to account for day-to-day variability in cognitive functioning. After cognitive assessments on visits one and three, participants underwent a fitness assessment on a cycle ergometer. Within the baseline period, sleep was measured for 5 nights, including at least one night of weekend sleep, using a take home device (WatchPAT™). Baseline visits were separated by at least 3 days to minimize practice and fatigue effects.

After baseline visits were complete, each participant underwent a single bout of acute high intensity cycling-based interval exercise, or a control condition where participants sat quietly for the same duration as the exercise session (29 minutes). Within 5 minutes of completing each condition, participants commenced cognitive assessment. Participants wore the WatchPAT™ device to measure sleep that night, and on the following morning participants returned to the laboratory to complete another cognitive assessment. Participants were asked to refrain from ingesting any substances that may impact sleep (the night before any session), and to maintain caffeine consumption within their usual habits the morning of all baseline and intervention sessions. For intervention sessions only, participants were also requested to refrain from any physical activity before the session.

Baseline measures

Cardiorespiratory fitness measure

To measure cardiorespiratory fitness, participants completed a cycling-based test on an electromagnetically braked cycle ergometer (Velotron, Racermate, Seattle, Washington, United States) to measure peak aerobic capacity (VO_{2peak}) and peak power output. A double baseline assessment of VO_{2peak} was conducted to gain the most accurate estimate of cardiorespiratory fitness (Tonino and Driscoll, 1988). The VO_{2peak} test protocol was based on Brown et al. (2017) and involved two-minute stages at incremental work rates no greater than two metabolic equivalents until exhaustion, based on the participants body mass. Participants >70 kg commenced at 30 W with increases of 20 W every stage. Participants between 70 and 100 kg commenced at 30 W with increases of 25 W every stage, and participants >100 kg commenced at 40 W with increases of 35 W every stage. The test was terminated at volitional exhaustion or when the cadence dropped below 60 revolutions per minute for 5 s. During the test, heart rate and ventilatory gasses were continuously recorded and averaged into 15-s intervals by a metabolic cart (TrueOne 2400, Parvomedics). VO_{2peak} was defined as the greatest 15-s mean value during the final 2 min of the test. Peak power output was calculated as the power at the last completed stage plus a pro-rata value of any uncompleted stage (Peiffer et al., 2008).

Self-report measures

Mood was measured using the Depression, Anxiety and Stress Scale (DASS; Lovibond and Lovibond, 1995). The PSQI was used to categorize individuals as 'poor sleepers' for inclusion, if their total score was >5, a threshold which has demonstrated high sensitivity and specificity (Backhaus et al., 2002). Years of education was determined via participant self-report and was a measure of full-time equivalent studies.

Cognitive assessment

Cognitive domains of interest for the current study include executive function, attention and episodic memory, as these domains are most consistently associated with sleep and exercise (Nouchi et al., 2014; Gildner et al., 2019). Composite scores were created for each cognitive domain using tasks from Cogstate, a computerized cognitive assessment (see www.cogstate.com). Cogstate was selected as opposed to traditional pen-and-paper assessments with the aim of reducing learning and ceiling effects (e.g., words on the Cogstate shopping list change at each administration, compared to the California Verbal Learning test where words remain the same). The episodic memory composite was formed from the Continuous Paired Associate Learning task (number of errors; reverse scored), International Shopping List test recall, and One Card Learning test. The attention composite included the Detection and Identification tasks, and the executive function composite included the One Back and Groton Maze Learning tasks.

Objective sleep assessment

A wrist-worn WatchPAT™ device (Itamar Medical, Caesarea, Israel) was used to measure baseline (5 nights, including at least one weekend night) and post-intervention sleep (one night). The WatchPAT™ device uses the peripheral arterial tone signal to detect sleep stages (Bresler et al., 2008). The WatchPAT™ has demonstrated

10.3389/fpsyg.2023.1207199

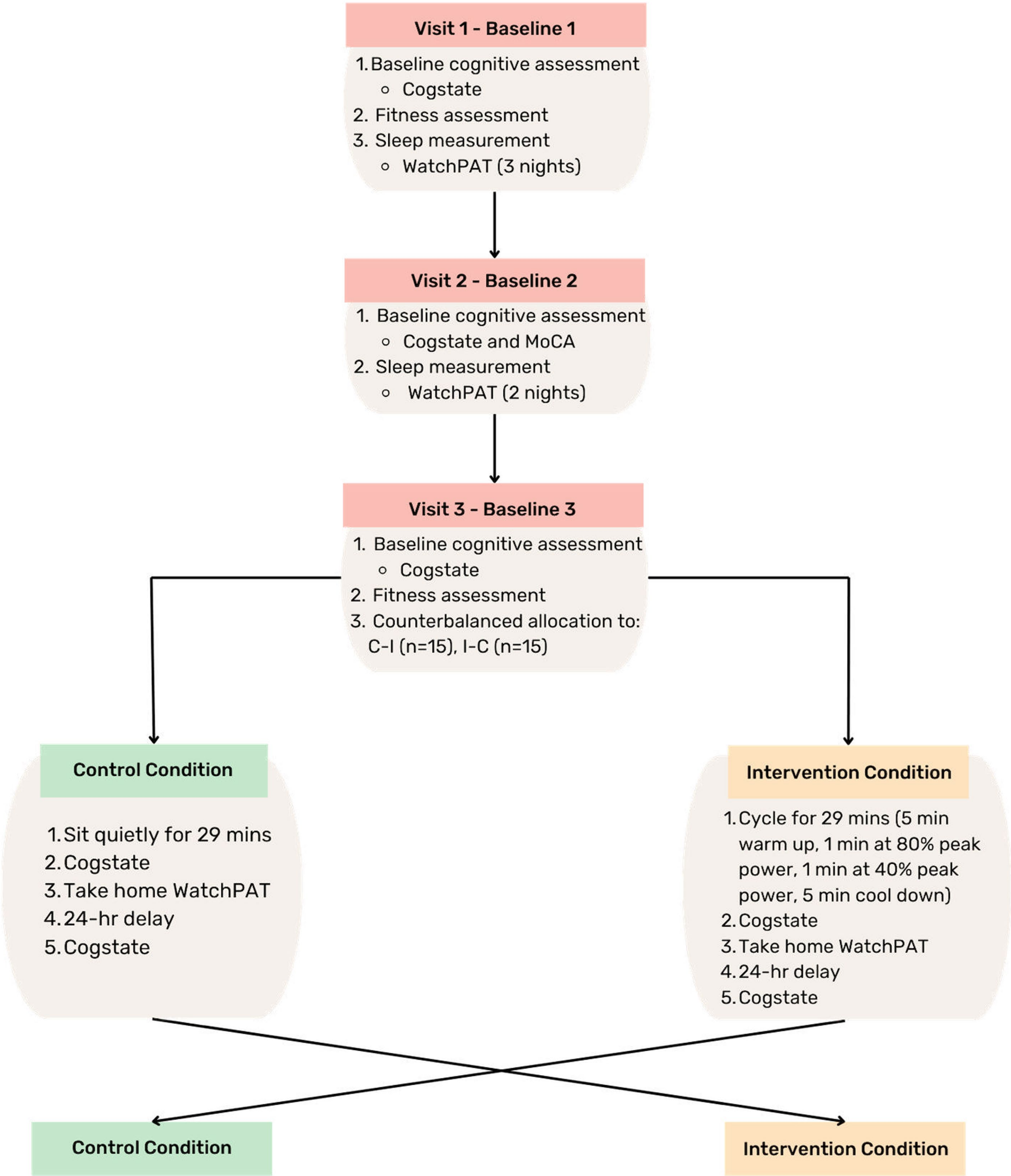


FIGURE 1
Study design. MoCA, Montreal Cognitive Assessment; C-I, control-intervention; I-C, intervention-control; min, minute; hr, hour.

sensitivity to detect light and deep sleep compared to the gold standard sleep measurement, polysomnography (80% agreement; Bresler et al., 2008). For the current study, measures of total sleep time (TST), sleep onset latency (in minutes), sleep efficiency (% of time in bed spent asleep), and % of REM sleep, light sleep (stages N1 and N2) and deep sleep (stage N3) were utilized. Scores were averaged over the five baseline nights to create a single baseline score for each sleep outcome of interest. If participants had missing baseline data, scores were averaged over the number of available nights of data (minimum 3 nights). Participants with more than two nights of missing sleep data were excluded from analyses which included sleep variables. A single night of sleep data was measured post-exercise and post-control. To account for night-to-night sleep variability, we included the within-participant standard deviation across baseline nights for each respective sleep variable as a covariate.

Exercise intervention protocol

Participants completed a 5-min warm-up at 40% peak power output (determined via the average peak power of baseline fitness assessments) on the Velotron ergometer followed by ten 1-min intervals at 80% peak power output interspaced with 1-min intervals at 40% peak power output. After the intervals, participants completed a 4-min cooldown at 40% peak power output. The individualized power outputs were pre-programmed into, and controlled by, the ergometer's built-in software.

Control condition protocol

During the control condition, participants were asked to sit quietly in a lab room for the same amount of time as the exercise protocol (29 min). Participants were not permitted to use personal devices during this time and were instead provided with a set of magazines to read. On the day of the control condition, participants were asked to refrain from exercise for the whole day.

Statistical analyses

All analyses were conducted in R Version 4.2.1 (R Core Team, 2022). To address Aim one, a linear mixed model was conducted using condition (control, intervention) as the predictor variable, and cognitive change scores, from baseline to post-intervention, as the dependent variable (separate models for each cognitive domain), with participant identification number entered as a random factor. To address Aim two, another linear mixed model was conducted using condition (control, intervention) as the predictor variable, and sleep outcome change score, from baseline to post-intervention, as the dependent variable, with participant identification number entered as a random factor. Separate models were run for each sleep outcome, namely: TST, sleep onset latency, sleep efficiency, REM sleep %, light sleep %, and deep sleep %. To address Aim three, a mediation analysis was conducted, using the PROCESS macro for R (Hayes, 2017). Condition was treated as the independent categorical variable, sleep change score (baseline to post-intervention) as the mediator variable, and cognitive change score (baseline to 24 h post-intervention) as the dependent variable (Figure 2). Separate models were run for each sleep variable on each cognitive outcome. Age, sex, baseline fitness (averaged over the two assessments), and standard deviation of the baseline sleep measure per participant were treated as covariates in all models. Years of education and DASS score were tested as additional covariates, however their inclusion reduced model fit, and thus due to our limited statistical power, they were excluded from all analyses. For significant outcomes (determined by $p < 0.05$) from Aims one and two, the false discovery rate (FDR) correction was applied (Benjamini and Yekutieli, 2001). Aim three was the proof-of-concept aspect of our analysis, and therefore an FDR correction was not applied (Armstrong, 2014). Accordingly, for these results, we examined confidence intervals and magnitude of change as opposed to statistical significance. All results which showed a significant change in cognitive outcomes (after correction, if required) were compared to the smallest detectable change (SDC) score, detailed below.

Previous recommendations for sample size of a pilot trial are at least 9% of the sample size of the main planned trial (Cocks and Torgerson, 2013). Based on Fritz and Mackinnon (2007), a trial conducted using mediation analysis would require a sample of $n = 116$ (using bootstrapped corrected estimates and medium effect sizes), meaning the required sample for the current trial is minimum $n = 10$. Other studies have recommended pilot samples of at least 12 per group (Julious, 2005) and so we aimed to recruit $n = 30$ to maximize statistical power within each group and to account for potential attrition.

One participant had missing sleep data from baseline (only one viable night) and post-intervention nights due to failure of the sleep measurement device, these data were consequently removed from all analyses which included sleep variables ($n = 29$ for these analyses). This participant was included in analyses which did not use sleep data (i.e., analyses for Aim one) to maximize statistical power. There were an additional total 5 instances where the sleep measurement device failed on either the exercise or control night. These missing data were removed from all sleep analyses, however the remaining participant data were utilized (i.e., if the device failed only on the control night for one participant, sleep data from the night following exercise were retained). This missing data constituted 8.6% of the entire dataset, and three instances were after the control condition, while two instances were after the exercise condition.

Smallest detectable change

The triple baseline cognitive assessment was utilized to calculate change in cognition from baseline to post-exercise, not due to measurement error or expected fluctuation in cognitive performance; i.e., we have calculated the smallest detectable change (SDC; Bland and Altman, 1986). This methodology has been adopted from previous research (Geerinck et al., 2019). Firstly, the standard error of the mean (SEM) was calculated by creating a difference score between the second and third baseline cognitive measurements for each participant (second score – third score = difference). The difference between baseline two and three was selected based on the rationale that any differences between the first and second baseline will most likely be due to practice effects, but these effects will have plateaued by the third cognitive assessment (Falleti et al., 2006). Next, the standard deviation for the "difference" variable was calculated and divided by the square root of 2, resulting in the SEM ($SEM = \frac{SD_{difference}}{\sqrt{2}}$). Individual SDC ($SDC_{ind}$) was then calculated using the following formula: $SDC_{ind} = 1.96 * \sqrt{2} * SEM$. Finally, the group SDC (SDC_{group}) was determined by dividing the SDC_{ind} by the square root of the number of subjects in the sample ($\frac{SCD_{ind}}{\sqrt{n}}$), yielding a single SDC_{group} score for each cognitive composite. This SDC_{group} score was used to indicate whether the post-exercise changes in cognition are meaningful, or whether they may be due to measurement error. Namely, any exercise-induced significant changes at the group level were compared to the SDC_{group} score. Further, because there is significant intra-individual variability in cognitive response to exercise, the SDC_{ind} for the respective cognitive variable was ± to/from each individual participant's "best score" across the baseline cognitive measurement. This methodology resulted in an individual

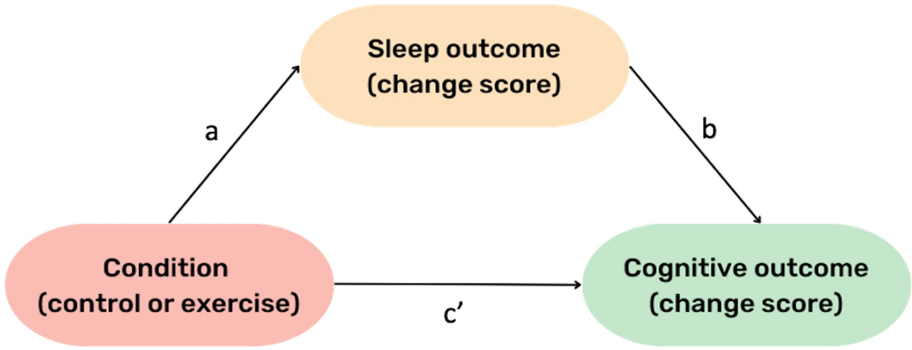


FIGURE 2
General Mediation Model. The "a" pathway represents the effect of condition (exercise vs. control) on change in the respective sleep outcome. The "b" pathway represents the effect of change in sleep on change in cognition, whilst holding condition constant (i.e., regardless of intervention condition). The c′ pathway represents the effect of intervention condition on cognition (~24 h later), while holding the respective sleep variable constant.

threshold which each participant would need to reach to achieve probable meaningful cognitive change.

Results

Baseline participant demographics are presented in Table 1. Briefly, the cohort had a mean age of 69.2 ± 4.3 years, was comprised of 66% females, and as per inclusion criteria, all participants were poor sleepers (>5 on the PSQI).

Effect of the exercise intervention on cognitive function and sleep

Linear mixed models showed no between condition differences (intervention vs. control) for change in any cognitive outcome from pre- to immediately post-intervention (Table 2). Similarly, there were no differences in changes in sleep variables between control and intervention conditions (Table 2).

Sleep as a mediator for associations between exercise intervention and cognition

Mediation analyses demonstrated no indirect effects of intervention condition on change in any cognitive domain through change in any sleep variable (Table 3). However, regardless of intervention condition, a small effect was observed where increases in deep sleep % from baseline predicted a positive change in episodic memory performance the following day ("b" pathway, Figure 2; $\beta = 0.03$, SE = 0.03, [95% CI 0.001–0.066]). Conversely, small increase in light sleep % from baseline predicted a small negative change in episodic memory performance the following day ("b" pathway, Figure 2; $\beta = -0.02$, SE = 0.01, [95% CI −0.04 to −0.004]). However, because this was a proof-of-concept aim, conclusions regarding statistical significance cannot be drawn.

TABLE 1 Participant characteristics (*n* = 30).

Demographics	Baseline
Age, mean (SD)	69.2 (4.3)
Sex, % female (*n*)	66.7 (20)
Years of education, mean (SD)	14 (2.7)
Mood (DASS score), mean (SD)	9.1 (4.7)
MoCA score, mean (SD)	26.4 (1.8)
Cardiorespiratory fitness (VO_{2peak})	23 (5.6)
Sleep medication use, % positive (*n*)	50 (15)
Total PSQI score, mean (SD), range	9.7 (2.6), 6–15
Sleep efficiency (%), mean (SD)	84.9 (5.3)
Total sleep time (hours), mean (SD)	6.5 (0.8)
Sleep onset latency (minutes), mean (SD)	19.5 (5.6)
Light sleep (%), mean (SD)	63.2 (8.6)
Deep sleep (%), mean (SD)	14.3 (4.3)
REM sleep (%), mean (SD)	22.5 (5.7)

DASS, Depression, Anxiety and Stress Scale; PSQI, Pittsburgh Sleep Quality Index; MoCA, Montreal Cognitive Assessment; REM, rapid eye movement. All sleep variables taken from baseline WatchPAT measurements, except for PSQI score which is self-reported. VO_{2peak} refers to peak aerobic capacity, averaged across two baseline fitness tests.

Smallest detectable change outcomes

At the group level, a cognitive composite score change of 0.24 for attention, 0.30 for executive function, and 0.32 for episodic memory is required to observe "true change" (SDC_{group}). At the individual level, a change of 1.34 for attention, 1.67 for executive function, and 1.80 for episodic memory is required to observe "true change" (SDC_{ind}). Figures 3–5 show individual participant change in episodic memory, executive function and attention cognitive composite scores, respectively, from baseline to immediately post-intervention, compared to their individual meaningful change threshold, calculated using the SDC_{ind}. Across a total of 60 assessments (one post-exercise, one post-control for each participant), participants showed meaningful change from baseline to immediately post-intervention for both episodic memory and executive

10.3389/fpsyg.2023.1207199

function 15% of the time, and for attention 42% of the time. Table 4 details these frequencies by intervention condition and categorized as "positive" or "negative" score change. Supplementary Figures S1–S3 and Supplementary Table S1 detail these same analyses for cognitive score change from baseline to 24-h post-intervention.

Discussion

The current study was intended as an exploratory, proof-of-concept trial to examine associations between acute exercise, objectively measured sleep, and cognitive function in cognitively unimpaired older adults. High intensity exercise did not affect any sleep variable, or cognitive function immediately post-exercise. For our proof-of-concept aim, we observed very little evidence for an indirect (mediating) effect of any sleep variable on associations between exercise and cognition (indicated by small effects and wide confidence intervals in Table 3). We did observe that regardless of acute exercise, small changes in light sleep % and deep sleep % from baseline to post-intervention were associated with changes in episodic memory from baseline to 24-h post-intervention, such that increased light sleep and decreased deep sleep were associated with poorer episodic memory.

We observed no influence of our acute exercise intervention on immediate cognitive performance, which is surprising given exercise can have immediate physiological and cognitive impacts (Coelho et al., 2014; Chang et al., 2019; McSween et al., 2019). Our results may be partially explained by the use of a triple baseline assessment of cognitive function. This methodology aimed to better account for variability in day-to-day cognitive functioning, as opposed to a single baseline measure (Bielak et al., 2017). As a result, any exercise-induced change in cognition may not have been large enough to differ significantly from natural intra-individual variability. Indeed, our individual analyses (see Figures 3–5) support this notion, showing that only a small number of individuals showed any meaningful change from baseline. Additionally, most previous studies conduct baseline cognitive assessments on the day of the intervention (e.g., Chang et al., 2014), which was not feasible in the current study due to the triple baseline measure (which could not be conducted on a single day, given that we wanted to utilize data from all three assessments in the baseline score). Finally, although participants in the current study were asked to maintain consistent caffeine and morning routine habits on the day of the session, there may be some variability (e.g., in social interactions) which could have influenced results (Bielak et al., 2017).

Contrary to our hypothesis, our results also showed no effect of exercise on any sleep variable, compared to baseline. These results are again unexpected, as previous research shows beneficial effects of acute exercise on multiple sleep parameters (Kredlow et al., 2015; Larsen et al., 2019). However, it should be noted that the effect sizes reported in Kredlow et al. were relatively small (Cohen's $d = 0.17$–0.25), thus the current study may have been underpowered to detect such changes (powered for $d = 0.60$). Additionally, we examined sleep change from baseline to post-intervention and compared to control, whereas previous studies have examined acute exercise vs. non-exercise days, without characterizing baseline sleep of the sample (Kredlow et al., 2015). Baseline comparisons are important in this context because of night-to-night sleep variability, which may be especially prevalent in older adults with sleep complaints (Kay et al., 2013). Although we did account for night-to-night sleep variability in our statistical analyses, large variability within some

TABLE 2 Linear mixed model analyses for the effect of condition (control vs. intervention) on sleep and cognitive outcomes (analyzed separately for each outcome).

Respective outcome	β	SE	*p*-value
Episodic memory	−0.05	0.18	0.776
Attention	−0.02	0.19	0.926
Executive function	−0.03	0.14	0.836
Total sleep time (hours)	0.10	0.20	0.617
Number of awakenings	1.43	0.83	0.091
Sleep onset latency (mins)	−3.47	2.73	0.210
Sleep efficiency (%)	0.39	0.95	0.686
REM sleep (%)	−0.44	1.50	0.772
Light sleep (%)	1.53	1.81	0.402
Deep sleep (%)	−0.88	0.95	0.361

β, Unstandardized Regression Coefficient; SE, Standard Error; REM, Rapid Eye Movement. Control condition used as reference group. Age, sex, baseline fitness and standard deviation of the respective sleep variable used as covariates in all models.

TABLE 3 Indirect effects of the intervention condition (control vs. exercise) on cognitive outcomes (change scores) through sleep variables (change scores).

	Executive function		Episodic memory		Attention	
	Effect	95% CI	Effect	95% CI	Effect	95% CI
Total sleep time (hours)	0.01	−0.05, 0.08	0.002	−0.06, 0.05	0.01	−0.07, 0.16
Number of awakenings	0.003	−0.13, 0.10	−0.03	−0.13, 0.05	−0.06	−0.23, 0.07
Sleep onset latency (mins)	0.04	−0.03, 0.14	0.05	−0.04, 0.19	0.06	−0.04, 0.25
Sleep efficiency (%)	0.001	−0.07, 0.06	0.002	−0.06, 0.04	0.02	−0.12, 0.17
REM sleep (%)	0.001	−0.04, 0.06	−0.01	−0.12, 0.07	−0.01	−0.14, 0.12
Light sleep (%)	0.02	−0.05, 0.11	−0.04	−0.18, 0.07	−0.03	−0.16, 0.12
Deep sleep (%)	0.03	−0.06, 0.14	−0.03	−0.17, 0.05	−0.04	−0.17, 0.08

CI, Confidence Interval; REM, Rapid Eye Movement. Control condition used as reference group. All models adjusted for age, sex, baseline fitness and baseline standard deviation of the respective sleep variable. Change scores refer to change from baseline to 24 h post intervention for cognition, and baseline to the night following intervention for sleep.

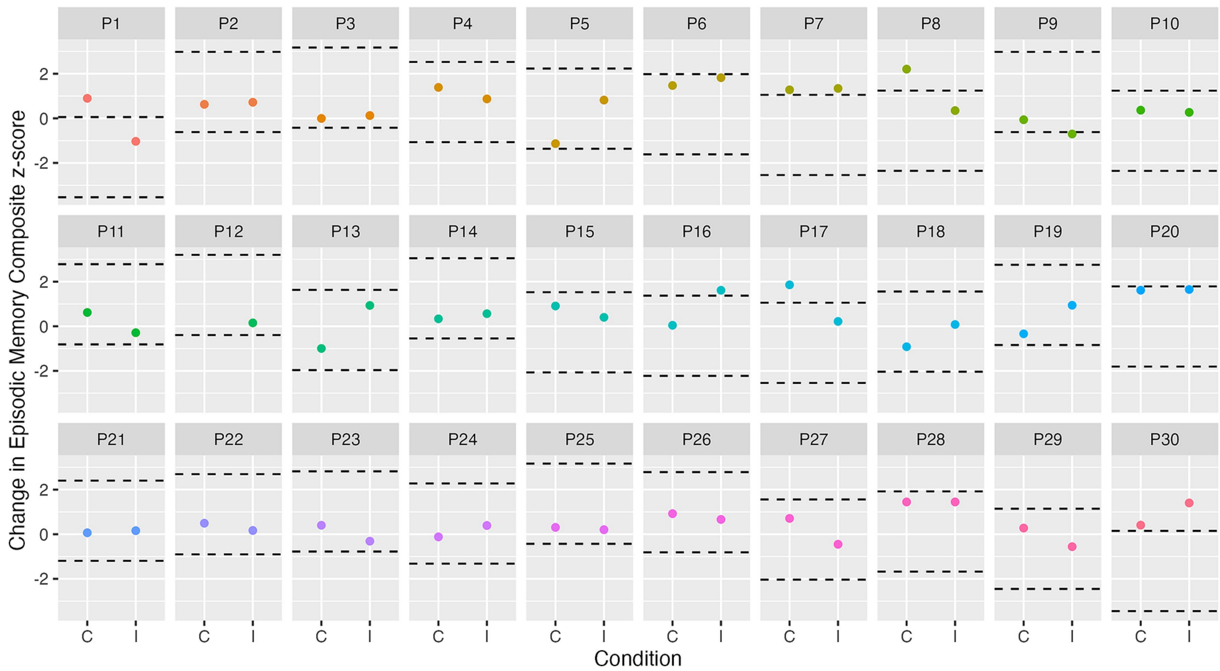


FIGURE 3
Individual change in episodic memory from baseline to immediately post-intervention. Dashed lines represent ± SDC_{ind} (z-score of 1.8) for episodic memory from each participant's best baseline episodic memory score. C, control condition; I, intervention condition; P, participant number.

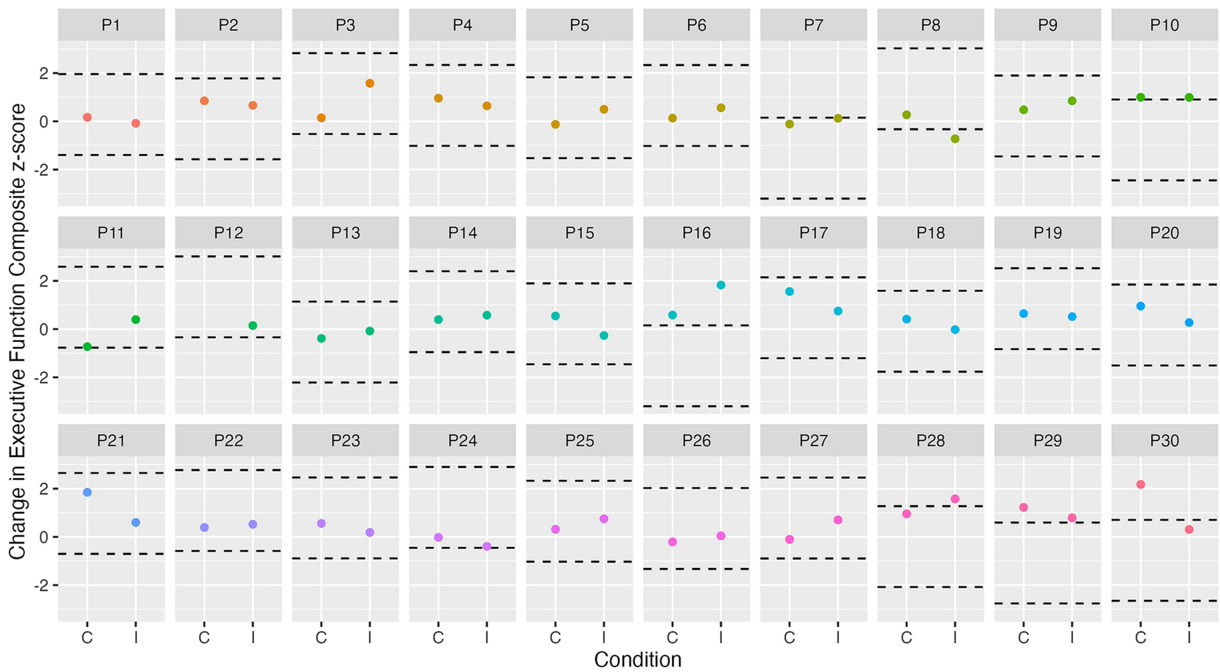


FIGURE 4
Individual change in executive function from baseline to immediately post-intervention. Dashed lines represent ± SDC_{ind} (z-score of 1.7) for executive function from each participant's best baseline executive function score. C, control condition; I, intervention condition; P, participant number.

participants may still influence overall findings, particularly within our small sample. Finally, the current study recruited individuals who were self-reported "poor" sleepers, however data from our objective measures showed sleep characteristics falling within the normal range (e.g., mean 6.5 h TST; mean 84.9% sleep efficiency). Indeed, previous research indicates that subjective and objective sleep assessments may measure, equally important, but different aspects of sleep; both are associated with health outcomes (Lou et al., 2015; Wirth et al., 2015;

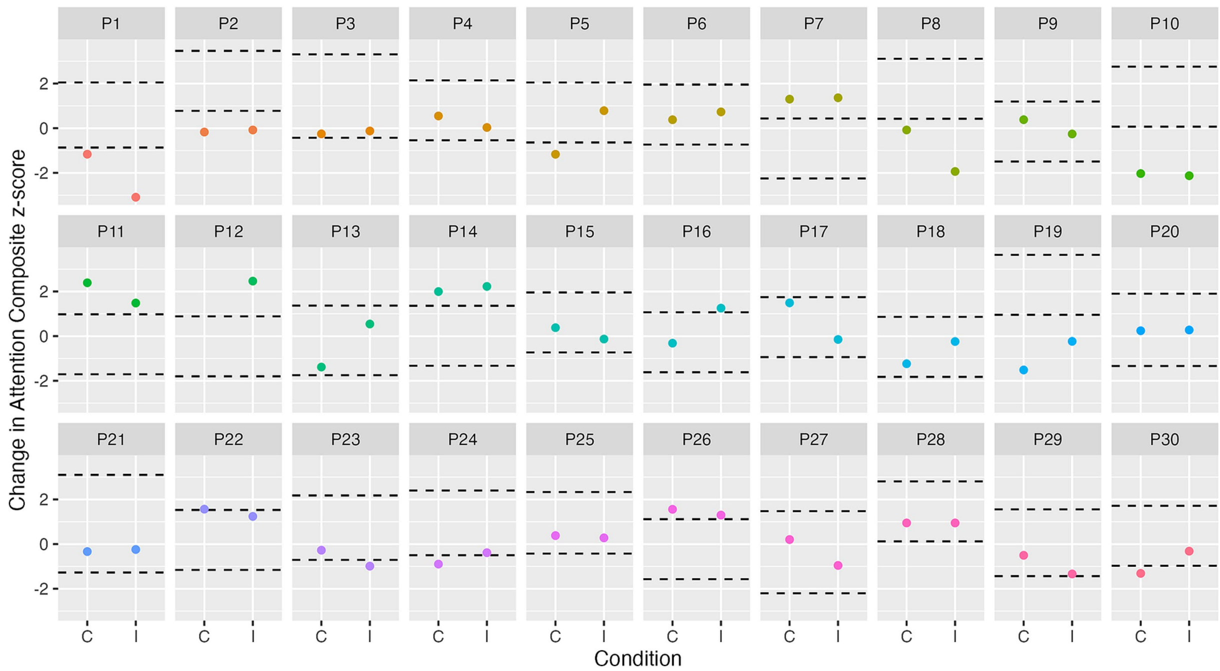


FIGURE 5
Individual change in attention from baseline to immediately post-intervention. Dashed lines represent ± SDC_{ind} (z-score of 1.3) for attention from each participant's best baseline attention score. C, control condition; I, intervention condition; P, participant number.

TABLE 4 Frequency table of meaningful cognitive change from baseline to immediately post-intervention.

	Episodic memory		Executive function		Attention	
	Control	Exercise	Control	Exercise	Control	Exercise
Increase	5	3	4	4	5	6
Decrease	0	1	0	1	8	6
No change	25	26	26	25	17	18

"Increase" means participants increased performance from baseline to a greater extent than the smallest detectable change. "Decrease" means participants decreased performance from baseline to a greater extent than the smallest detectable change. "No change" means participants change score fell within the range of the smallest detectable change.

Sewell et al., 2021). Thus, the discrepancy between objective and subjective sleep in the current research may partially explain our null results, as our exercise intervention may not have been sufficient to induce detectable changes in sleep. Further research is needed to examine the effects of both acute and chronic exercise on objectively measured sleep in a larger sample of older adults, using both objective and self-report sleep measures, considering night-to-night sleep variability.

In contrast to previous research (Wilckens et al., 2018; Cheval et al., 2022), we observed very little change in sleep and cognition from our exercise intervention, indicating there was not a mediating (indirect) effect. These results may be due to the lack of effect of exercise on sleep ("a" pathway, Figure 2), as we did observe associations between sleep and cognition ("b" pathway, Figure 2). Potential explanations of the null effect of exercise on sleep in our cohort are detailed above. However, it is important to consider that this is the first experimental study to test a mediating effect of sleep on associations between exercise and cognition, and was intended as a proof-of-concept trial, thus we cannot draw conclusions regarding statistical significance. From our results we see that the magnitude of our indirect effects was very small (Table 3). One previous observational study also reported null indirect effects for the impact of physical activity on cognition through sleep (Yuan et al., 2020). Thus, it is crucial to further test this mediation model using objectively measured sleep in an experimental design to determine cause-effect associations between these variables. Such studies should employ larger sample sizes because the effect size of exercise on sleep is already relatively small (Kredlow et al., 2015), and combined with the requirement of large samples to detect a mediating effect, power is an important consideration for such trials (Fritz and Mackinnon, 2007). Such power would also allow for statistical consideration of sleep variability, omission of which may contribute to a null effect of exercise on sleep.

From our mediation analysis, we observed that, regardless of exercise, sleep may be related to cognition. Specifically, small increases in deep sleep % (stage N3) from baseline to post-intervention were associated with small improvements in episodic memory, whereas increased light sleep % (stages N1 and N2) was associated with poorer episodic memory performance. Again, because this was a proof-of-concept trial, we cannot make decisions regarding statistical significance. However, these results are consistent with the broader literature which shows that habitual sleep is associated with cognitive function (Scullin and Bliwise, 2015; Dzierzewski et al., 2018). More specifically, a recent meta-analysis showed that memory and executive function are the two cognitive domains most frequently associated with sleep parameters, in both single-night and multi-night studies (Qin et al., 2023). However, in contrast to the current results, this meta-analysis did not examine associations between light sleep % and specific cognitive domains (due to a lack of studies investigating these relationships). Importantly, many studies in this area have not examined change in sleep from a baseline characterization, which is important because of night-to-night sleep variability. Thus, our study builds on the current literature by showing that changes in specific sleep stages may be associated with change in particular cognitive domains, however further research which is adequately powered to test such hypotheses is required. Despite associations between deep sleep and memory in older adults being inconsistent in previous studies (Qin et al., 2023), the current study supports the overall notion that age-related decreases in deep sleep % and increases in light sleep % are associated with negative changes in memory. Further research is required to characterize longitudinal associations between age-related changes in sleep and cognitive function.

In the current study, we utilized a triple baseline cognitive assessment with the aim of overcoming measurement error and accounting for natural variability in cognitive performance. Our group level analyses showed no exercise-induced cognitive change, and examining individual level data showed a small number of individual performance increase (see Figures 3–5; Table 4). However, our results do provide an indication of the smallest meaningful change needed for future studies using Cogstate to assess cognition in similar cognitively unimpaired older adult populations. The SDC_{group} and SDC_{ind} scores determined in this study for each cognitive composite may be utilized in future research to determine if post-intervention change is meaningful. For example, our SDC_{group} results showed that a change of 0.32 z-score units is required on our episodic memory composite score to be confident that such change is not due to measurement error. Based on our results from the mediation analysis, an approximate 10% change in deep sleep from baseline to post-intervention would be required to produce a 0.32-unit change in the episodic memory composite score. Similarly, an approximate 16% change in light sleep would be required to produce this change in episodic memory. Given the average variability across baseline sleep nights was 2.98% for deep sleep, and 5.86% for light sleep, the required change is quite large, and would be unlikely to occur acutely in the current sample. These results support the notion that the effects of sleep on cognition may be relatively small in an acute setting, in a population of cognitively unimpaired older adults who report poor sleep, and highlight the need for future studies to better quantify observed cognitive change, and consider whether such change is meaningful.

We acknowledge that this proof-of-concept study is subject to limitations, including small sample size, resulting in limited power to detect a mediating effect of sleep on the relationship between exercise and cognition. Given that there is cross-sectional evidence for a mediating effect of sleep on the relationship between exercise and cognition, future studies should consider testing this model in a larger sample, with a chronic exercise intervention. Further, the use of a chronic exercise intervention would allow additional nights of sleep measurement post-intervention, as opposed to the single night measure in the current study. Our sample was also relatively homogenous, comprising highly motivated, highly educated, and physically active individuals. However, we did utilize a well-validated objective sleep measure with the ability to examine sleep staging, a comprehensive cognitive assessment with a triple baseline, and a fully supervised exercise intervention. Moreover, while we were not able to control whether participants exercised on days where baseline sleep was measured, we did account for this using a physical activity diary.

The current study showed that an acute high intensity exercise intervention did not yield immediate post-intervention impacts on cognition or sleep in cognitively unimpaired older adults with self-reported poor sleep. However, sleep appears to be associated with cognition independently of acute exercise; an association which may be dependent upon the specific sleep and cognitive variables being examined. Further research is required to elucidate associations between exercise, sleep and cognition in older adults, namely examining a mediating effect of sleep in chronic exercise intervention studies. Such research should also consider potential biological explanations for these associations, e.g., levels of brain-derived neurotropic factor (BDNF) which are influenced by both sleep and exercise. This type of research will contribute to knowledge of the most effective interventions for preserving cognitive function in our aging population.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Murdoch University Human Research Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

KS contributed to data collection, conception of the project, data analysis, drafting, and revising manuscript. NS contributed to project design and data collection, and wrote sections of the manuscript. SR-S, HS, JP, and KE contributed to conception and design of the project and data interpretation. BB contributed to supervision, study design, data interpretation, and wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

Acknowledgments

KS is supported by the Australian Government Research Training Program (RTP) Scholarship. SR-S is supported by an NHMRC Investigator Grant (GNT1197315). This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. All authors would like to thank the study participants for their generous participation and contribution of time.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1207199/full#supplementary-material

References

Angevaren, M., Vanhees, L., Wendel-Vos, W., Verhaar, H. J. J., Aufdemkampe, G., Aleman, A., et al. (2007). Intensity, but not duration, of physical activities is related to cognitive function. *Eur. J. Cardiovasc. Prev. Rehabil.* 14, 825–830. doi: 10.1097/hjr.0b013e3282ef995b

Armstrong, R. A. (2014). When to use the Bonferroni correction. *Ophthalmic Physiol. Opt.* 34, 502–508. doi: 10.1111/opo.12131

Backhaus, J., Junghanns, K., Broocks, A., Riemann, D., and Hohagen, F. (2002). Test–retest reliability and validity of the Pittsburgh sleep quality index in primary insomnia. *J. Psychosom. Res.* 53, 737–740. doi: 10.1016/S0022-3999(02)00330-6

Benjamini, Y., and Yekutieli, D. (2001). The control of the false discovery rate in multiple testing under dependency. *Ann. Stat.* 29, 1165–1188. doi: 10.1214/aos/1013699998

Bielak, A. A. M., Mogle, J., and Sliwinski, M. J. (2017). What did you do today? Variability in daily activities is related to variability in daily cognitive performance. *J. Gerontol. Ser. B* 74, 764–771. doi: 10.1093/geronb/gbx145

Bland, J. M., and Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 327, 307–310. doi: 10.1016/S0140-6736(86)90837-8

Blondell, S. J., Hammersley-Mather, R., and Veerman, J. L. (2014). Does physical activity prevent cognitive decline and dementia? A systematic review and meta-analysis of longitudinal studies. *BMC Public Health* 14:510. doi: 10.1186/1471-2458-14-510

Boyce, R., Williams, S., and Adamantidis, A. (2017). REM sleep and memory. *Curr. Opin. Neurobiol.* 44, 167–177. doi: 10.1016/j.conb.2017.05.001

Bresler, M., Sheffy, K., Pillar, G., Preiszler, M., and Herscovici, S. (2008). Differentiating between light and deep sleep stages using an ambulatory device based on peripheral arterial tonometry. *Physiol. Meas.* 29, 571–584. doi: 10.1088/0967-3334/29/5/004

Brown, B. M., Peiffer, J. J., Sohrabi, H. R., Mondal, A., Gupta, V. B., Rainey-Smith, S. R., et al. (2012). Intense physical activity is associated with cognitive performance in the elderly. *Transl. Psychiatry* 2:e191. doi: 10.1038/tp.2012.118

Brown, B. M., Rainey-Smith, S. R., Castalanelli, N., Gordon, N., Markovic, S., Sohrabi, H. R., et al. (2017). Study protocol of the intense physical activity and cognition study: the effect of high-intensity exercise training on cognitive function in older adults. *Alzheimer's Dement. Transl. Res. Clin. Intervent.* 3, 562–570. doi: 10.1016/j.trci.2017.09.003

Bubu, O. M., Brannick, M., Mortimer, J., Umasabor-Bubu, O., Sebastião, Y. V., Wen, Y., et al. (2016). Sleep, cognitive impairment, and Alzheimer's disease: a systematic review and meta-analysis. *Sleep* 40:zsw032. doi: 10.1093/sleep/zsw032

Caspersen, C. J., Powell, K. E., and Christenson, G. M. (1985). Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. *Public Health Rep.* 100, 126–131. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1424733/.

Chang, Y.-K., Chen, F.-T., Kuan, G., Wei, G.-X., Chu, C.-H., Yan, J., et al. (2019). Effects of acute exercise duration on the inhibition aspect of executive function in late middle-aged adults. *Front. Aging Neurosci.* 11:227. doi: 10.3389/fnagi.2019.00227

Chang, Y.-K., Chi, L., Etnier, J. L., Wang, C.-C., Chu, C.-H., and Zhou, C. (2014). Effect of acute aerobic exercise on cognitive performance: role of cardiovascular fitness. *Psychol. Sport Exerc.* 15, 464–470. doi: 10.1016/j.psychsport.2014.04.007

Cheval, B., Maltagliati, S., Sieber, S., Cullati, S., Zou, L., Ihle, A., et al. (2022). Better subjective sleep quality partly explains the association between self-reported physical activity and better cognitive function. *J. Alzheimer's Dis.* 87, 919–931. doi: 10.3233/JAD-215484

Cocks, K., and Torgerson, D. J. (2013). Sample size calculations for pilot randomized trials: a confidence interval approach. *J. Clin. Epidemiol.* 66, 197–201. doi: 10.1016/j.jclinepi.2012.09.002

Coelho, F. G., Vital, T. M., Stein, A. M., Arantes, F. J., Rueda, A. V., Camarini, R., et al. (2014). Acute aerobic exercise increases brain-derived neurotrophic factor levels in elderly with Alzheimer's disease. *J. Alzheimers Dis.* 39, 401–408. doi: 10.3233/JAD-131073

Dzierzewski, J. M., Dautovich, N., and Ravyts, S. (2018). Sleep and cognition in older adults. *Sleep Med. Clin.* 13, 93–106. doi: 10.1016/j.jsmc.2017.09.009

Erickson, K. I., Donofry, S. D., Sewell, K. R., Brown, B. M., and Stillman, C. M. (2022). Cognitive aging and the promise of physical activity. *Annu. Rev. Clin. Psychol.* 18, 417–442. doi: 10.1146/annurev-clinpsy-072720-014213

Falleti, M. G., Maruff, P., Collie, A., and Darby, D. G. (2006). Practice effects associated with the repeated assessment of cognitive function using the CogState battery at 10-minute, one week and one month test-retest intervals. *J. Clin. Exp. Neuropsychol.* 28, 1095–1112. doi: 10.1080/13803390500205718

Fritz, M. S., and Mackinnon, D. P. (2007). Required sample size to detect the mediated effect. *Psychol. Sci.* 18, 233–239. doi: 10.1111/j.1467-9280.2007.01882.x

Geerinck, A., Alekna, V., Beaudart, C., Bautmans, I., Cooper, C., De Souza Orlandi, F., et al. (2019). Standard error of measurement and smallest detectable change of the sarcopenia quality of life (SarQoL) questionnaire: an analysis of subjects from 9 validation studies. *PLoS One* 14:e0216065. doi: 10.1371/journal.pone.0216065

Gildner, T. E., Salinas-Rodríguez, A., Manrique-Espinoza, B., Moreno-Tamayo, K., and Kowal, P. (2019). Does poor sleep impair cognition during aging? Longitudinal associations between changes in sleep duration and cognitive performance among older Mexican adults. *Arch. Gerontol. Geriatr.* 83, 161–168. doi: 10.1016/j.archger.2019.04.014

Haskell, W. L., Lee, I.-M., Pate, R. R., Powell, K. E., Blair, S. N., Franklin, B. A., et al. (2007). Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Med. Sci. Sports Exerc.* 39, 1423–1434. doi: 10.1249/mss.0b013e3180616b27

Hayes, A. F. (2017). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. New York, NY, USA: Guilford publications.

Julious, S. A. (2005). Sample size of 12 per group rule of thumb for a pilot study. *Pharm. Stat.* 4, 287–291. doi: 10.1002/pst.185

Kay, D. B., Dzierzewski, J. M., Rowe, M., and McCrae, C. S. (2013). Greater night-to-night variability in sleep discrepancy among older adults with a sleep complaint compared to noncomplaining older adults. *Behav. Sleep Med.* 11, 76–90. doi: 10.1080/15402002.2011.602775

Kredlow, M. A., Capozzoli, M. C., Hearon, B. A., Calkins, A. W., and Otto, M. W. (2015). The effects of physical activity on sleep: a meta-analytic review. *J. Behav. Med.* 38, 427–449. doi: 10.1007/s10865-015-9617-6

Lambiase, M. J., Gabriel, K. P., Kuller, L. H., and Matthews, K. A. (2014). Sleep and executive function in older women: the moderating effect of physical activity. *J. Gerontol. Ser. A* 69, 1170–1176. doi: 10.1093/gerona/glu038

Larsen, P., Marino, F., Melehan, K., Guelfi, K. J., Duffield, R., and Skein, M. (2019). High-intensity interval exercise induces greater acute changes in sleep, appetite-related hormones, and free-living energy intake than does moderate-intensity continuous exercise. *Appl. Physiol. Nutr. Metab.* 44, 557–566. doi: 10.1139/apnm-2018-0503

Lou, P., Qin, Y., Zhang, P., Chen, P., Zhang, L., Chang, G., et al. (2015). Association of sleep quality and quality of life in type 2 diabetes mellitus: a cross-sectional study in China. *Diabetes Res. Clin. Pract.* 107, 69–76. doi: 10.1016/j.diabres.2014.09.060

Lovibond, P. F., and Lovibond, S. H. (1995). The structure of negative emotional states: comparison of the depression anxiety stress scales (DASS) with the Beck depression and anxiety inventories. *Behav. Res. Ther.* 33, 335–343. doi: 10.1016/0005-7967(94)00075-U

McSween, M.-P., Coombes, J. S., Mackay, C. P., Rodriguez, A. D., Erickson, K. I., Copland, D. A., et al. (2019). The immediate effects of acute aerobic exercise on cognition in healthy older adults: a systematic review. *Sports Med.* 49, 67–82. doi: 10.1007/s40279-018-01039-9

Nakakubo, S., Makizako, H., Doi, T., Tsutsumimoto, K., Lee, S., Lee, S., et al. (2017). Impact of poor sleep quality and physical inactivity on cognitive function in community-dwelling older adults. *Geriatr Gerontol Int* 17, 1823–1828. doi: 10.1111/ggi.12973

Nouchi, R., Taki, Y., Takeuchi, H., Sekiguchi, A., Hashizume, H., Nozawa, T., et al. (2014). Four weeks of combination exercise training improved executive functions, episodic memory, and processing speed in healthy elderly people: evidence from a randomized controlled trial. *Age (Dordr.)* 36, 787–799. doi: 10.1007/s11357-013-9588-x

Oberste, M., Javelle, F., Sharma, S., Joisten, N., Walzik, D., Bloch, W., et al. (2019). Effects and moderators of acute aerobic exercise on subsequent interference control: a systematic review and Meta-analysis. *Front. Psychol.* 10:2616. doi: 10.3389/fpsyg.2019.02616

Peiffer, J. J., Abbiss, C. R., Chapman, D., Laursen, P. B., and Parker, D. L. (2008). Physiological characteristics of masters-level cyclists. *J. Strength Cond. Res.* 22, 1434–1440. doi: 10.1519/JSC.0b013e318181a0d2

Pendlebury, S. T., Welch, S. J. V., Cuthbertson, F. C., Mariz, J., Mehta, Z., and Rothwell, P. M. (2013). Telephone assessment of cognition after transient ischemic attack and stroke. *Stroke* 44, 227–229. doi: 10.1161/STROKEAHA.112.673384

Qin, S., Leong, R. L. F., Ong, J. L., and Chee, M. W. L. (2023). Associations between objectively measured sleep parameters and cognition in healthy older adults: a meta-analysis. *Sleep Med. Rev.* 67:101734. doi: 10.1016/j.smrv.2022.101734

R Core Team (2022). *R: A language and environment for statistical computing* R Foundation for Statistical Computing Available at: https://www.R-project.org/.

Rossetti, H., Lacritz, L., Cullum, M., and Weiner, M. (2011). Normative data for the Montreal cognitive assessment (MoCA) in a population-based sample. *Neurology* 77, 1272–1275. doi: 10.1212/WNL.0b013e318230208a

Scullin, M. K., and Bliwise, D. L. (2015). Sleep, cognition, and normal aging: integrating a half century of multidisciplinary research. *Perspect. Psychol. Sci.* 10, 97–137. doi: 10.1177/1745691614556680

Sewell, K. R., Erickson, K. I., Rainey-Smith, S. R., Peiffer, J. J., Sohrabi, H. R., and Brown, B. M. (2021). Relationships between physical activity, sleep and cognitive function: a narrative review. *Neurosci. Biobehav. Rev.* 130, 369–378. doi: 10.1016/j.neubiorev.2021.09.003

Sewell, K. R., Rainey-Smith, S. R., Peiffer, J., Sohrabi, H. R., Taddei, K., Ames, D., et al (2023a). The relationship between objective physical activity and change in cognitive function. *Alzheimers Dement.* 19, 2984–2993. doi: 10.1002/alz.12950

Sewell, K. R., Rainey-Smith, S. R., Villemagne, V. L., Peiffer, J., Sohrabi, H. R., Taddei, K., et al. (2023b). The interaction between physical activity and sleep on cognitive function and brain beta-amyloid in older adults. *Behav. Brain Res.* 437:114108. doi: 10.1016/j.bbr.2022.114108

Sink, K. M., Espeland, M. A., Castro, C. M., Church, T., Cohen, R., Dodson, J. A., et al. (2015). Effect of a 24-month physical activity intervention vs health education on cognitive outcomes in sedentary older adults: the LIFE randomized trial. *JAMA* 314, 781–790. doi: 10.1001/jama.2015.9617

Sofi, F., Valecchi, D., Bacci, D., Abbate, R., Gensini, G. F., Casini, A., et al. (2011). Physical activity and risk of cognitive decline: a meta-analysis of prospective studies. *J. Intern. Med.* 269, 107–117. doi: 10.1111/j.1365-2796.2010.02281.x

Tonino, R. P., and Driscoll, P. A. (1988). Reliability of maximal and submaximal parameters of treadmill testing for the measurement of physical training in older persons. *J. Gerontol.* 43, M101–M104. doi: 10.1093/geronj/43.4.M101

Westerberg, C. E., Florczak, S. M., Weintraub, S., Mesulam, M. M., Marshall, L., Zee, P. C., et al. (2015). Memory improvement via slow-oscillatory stimulation during sleep in older adults. *Neurobiol. Aging* 36, 2577–2586. doi: 10.1016/j.neurobiolaging.2015.05.014

Wilckens, K. A., Erickson, K. I., and Wheeler, M. E. (2018). Physical activity and cognition: a mediating role of efficient sleep. *Behav. Sleep Med.* 16, 569–586. doi: 10.1080/15402002.2016.1253013

Wirth, M. D., Hébert, J. R., Hand, G. A., Youngstedt, S. D., Hurley, T. G., Shook, R. P., et al. (2015). Association between actigraphic sleep metrics and body composition. *Ann. Epidemiol.* 25, 773–778. doi: 10.1016/j.annepidem.2015.05.001

Won, J., Alfini, A. J., Weiss, L. R., Nyhuis, C. C., Spira, A. P., Callow, D. D., et al. (2019). Caudate volume mediates the interaction between total sleep time and executive function after acute exercise in healthy older adults. *Brain Plasticity* 5, 69–82. doi: 10.3233/bpl-190087

Yoneda, T., Lewis, N. A., Knight, J. E., Rush, J., Vendittelli, R., Kleineidam, L., et al. (2021). The importance of engaging in physical activity in older adulthood for transitions between cognitive status categories and death: a coordinated analysis of 14 longitudinal studies. *J. Gerontol. A Biol. Sci. Med. Sci.* 76, 1661–1667. doi: 10.1093/gerona/glaa268

Young, J., Angevaren, M., Rusted, J., and Tabet, N. (2015). Aerobic exercise to improve cognitive function in older people without known cognitive impairment. *Cochrane Database Syst. Rev.* 4:CD005381. doi: 10.1002/14651858.cd005381.pub4

Yuan, M., Fu, H., Liu, R., and Fang, Y. (2020). Effect of frequency of exercise on cognitive function in older adults: serial mediation of depression and quality of sleep. *Int. J. Environ. Res. Public Health* 17:709. doi: 10.3390/ijerph17030709

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 05 January 2024
DOI 10.3389/fpsyg.2023.1256743

Check for updates

OPEN ACCESS

EDITED BY
Yaira Barranco-Ruiz,
University of Granada, Spain

REVIEWED BY
Pierluigi Diotaiuti,
University of Cassino, Italy
André Luiz Monezi Andrade,
Pontifical Catholic University of Campinas,
Brazil

*CORRESPONDENCE
Haiyun Wang
✉ 20141002@gcc.edu.cn
Guan Yang
✉ yangmp6@scut.edu.cn

†These authors have contributed equally to this work and share first authorship

RECEIVED 19 July 2023
ACCEPTED 11 December 2023
PUBLISHED 05 January 2024

CITATION
Ke Y, Liu X, Xu X, He B, Wang J, Zuo L, Wang H and Yang G (2024) Self-esteem mediates the relationship between physical activity and smartphone addiction of Chinese college students: a cross-sectional study. *Front. Psychol.* 14:1256743. doi: 10.3389/fpsyg.2023.1256743

Self-esteem mediates the relationship between physical activity and smartphone addiction of Chinese college students: a cross-sectional study

Yuanyuan Ke[1†], Xiuxia Liu[2†], Xue Xu[3], Bingchen He[1], Jinfu Wang[1], Lijun Zuo[1], Haiyun Wang[4*] and Guan Yang[1*]

[1]School of Physical Education, South China University of Technology, Guangzhou, Guangdong, China, [2]Department of Physical Education, Xiamen University, Xiamen, Fujian, China, [3]School of Finance and Economy, Guangdong Engineering Polytechnic, Guangzhou, Guangdong, China, [4]School of Physical Education, Guangzhou College of Commerce, Guangzhou, Guangdong, China

Objective: Smartphone addiction, as a key topic in the current field of behavioral addictions and public health, has brought many negative impacts on the physical, psychological, interpersonal communication, and even academic performance among contemporary college students. Therefore, the purpose of this study is to offer ideas for solving smartphone addiction among college students through investigating the potential mediating effect of self-esteem in the relationship between physical activity and smartphone addiction.

Methods: By the quota sampling, a cross-sectional study was conducted to investigate 650 college students from 10 colleges in Guangzhou Higher Mega Center, and several self-reported instruments including physical activity rating scale-3 (PARS-3), mobile phone addiction tendency scale (MPATS), self-esteem scale (SES) were used to collect the related data needed for the present study. The descriptive analysis, correlation analysis, hierarchical regression analysis, and mediating effect analysis in this study were performed in turn.

Results: The results showed that physical activity ($r = -0.124$, $p < 0.01$) and self-esteem ($r = -0.360$, $p < 0.01$) were all negatively correlated with smartphone addiction, and both could also significantly and negatively predict smartphone addiction. There was a positive correlation between physical activity and self-esteem ($r = 0.084$, $p < 0.05$), and self-esteem could be significantly predicted by physical activity. And more important, the relationship between physical activity and smartphone addiction could be partially mediated by self-esteem, and the indirect effect value was −0.346 (95% Boot CI = −0.695; −0.023), along with the mediating effect accounted for 24% of the total effect between physical activity and smartphone addiction.

Conclusion: The current study shows that physical activity could not only directly reduce smartphone addiction, but also decrease smartphone addiction by indirectly improving self-esteem, which is important in practice for solving this troublesome issue and then gradually developing a healthy behavior in daily life for college students in China, and even across the world in near future.

KEYWORDS

behavioral addiction, smartphone addiction, physical activity, self-esteem, mediating effect, college students, a cross-sectional study

1 Introduction

As an indispensable and practicable tool, smartphones have gradually penetrated into various aspects of people's daily life, such as social interaction, entertainment, office work, shopping, and wealth management (Gökçearslan et al., 2016). However, while smartphones bring considerable conveniences to human beings, the problem of smartphone addiction caused by excessive usage or pathological usage with smartphones has been also paid much attention for us (Yang et al., 2021). Nowadays, smartphone addiction is ubiquitously used among citizens, especially the population of college students (Jun, 2016; Chen et al., 2022). The previous research shows that the rate of smartphone addiction among teenagers has exceeded 25% in China (Tang et al., 2016), which is higher than that in global youth with 23.3% (Sohn et al., 2019), and likewise, the prevalence of mobile phone addiction in the group of college students ranges from 21.4 to 27.4% (Jun, 2016). As we all know, smartphone addiction not only leads to poor academic performance and sleep quality among college students (Li et al., 2015; Hawi and Samaha, 2016; Rathakrishnan et al., 2021; Kao, 2023), but also brings a series of mental health problems to them, such as anxiety, depression, loneliness, as well as the poor interpersonal relationships (Jun, 2016; Kim and Kim, 2016; Wang et al., 2017; Diotaiuti et al., 2021; Ou-Yang et al., 2022). It is admittedly that owing to the serious negative effect from the COVID-19 Lockdown in recent years, the issue that college students' psychological adjustment and reaction during facing this emergent incident has been greatly attracted a large number of attention by researchers at alien and domestic now (Diotaiuti et al., 2021), and in particular, those individuals who have largely addicted themselves to the these advanced digital communicating devices, such as the computers and smartphones (Diotaiuti et al., 2022a,b).

Obviously, due to smartphone addiction has caused serious problems on the physical and mental health for college students, and therefore, how to prevent it or solve it has become an important challenge for us now. Fortunately, some preceding studies have disclosed that a significant and negative correlation was between physical activity and smartphone addiction (Choi, 2015; Kim et al., 2015; Yang et al., 2019; Lin et al., 2022). physical activity, as a manner of physical exercise with a certain intensity, frequency, and duration (Liu, 2020), can not only improve physical fitness, but also greatly contribute to mental health (Ho et al., 2015). According to the theory of temporal self-regulation of physical activity (Salmon, 2001; Chen et al., 2022), many behaviors beneficial for the individual body are usually generated by regular physical activity, and it can be easily seen that reasonably increasing physical activity plays an important role in personal health. Yang et al. (2021) pointed out that the higher level of physical activity means the lower probability of smartphone addiction for college students in their daily life; and the author also put forth that moderate-intensity acute aerobic exercise could reduce college students' desire for mobile phones (Yang et al., 2022). That is, physical activity could reduce the probability of addiction to smartphones in some degree. Based on these persuasive evidence above, it is not difficult to detect that there is a negative correlation between physical activity and smartphone addiction, which means actively engaging in physical activity in daily life could effectively reduce the possibility of addicting to smartphones.

Self-esteem, as an individual's evaluation of their self-worth and a positive or negative attitude toward themselves (Baumeister et al., 2003), has been closely related to mental health for human beings (Gao et al., 2015; Ding et al., 2020). As one of the valid assessment indicators for mental health, self-esteem has a very significant impact on the comprehensive development among college students. However, the fear management theory of self-esteem points out that when the persons encounter adverse environments that are not conducive to the development of self-esteem, they would use some specific methods to self-compensate; specifically speaking, the greater threat from self-esteem for them, the more likely to engage in problematic or abnormal behavior to compensate themselves, including smartphone dependency (Yang et al., 2004; He et al., 2020). In other words, when college students' self-esteem may not be satisfied in time, they probably use mobile phones to compensate themselves, which ultimately leads to a severe issue, namely smartphone addiction. Consistent with the published research, individuals with low self-esteem would be more likely to develop smartphone addiction (Sung, 2014; He et al., 2019; Zeidan et al., 2021). Undoubtedly, based on these studies above, it can be easily proposed that self-esteem is negatively correlated with smartphone addiction in a large degree.

As an essential topic in the field of sports and exercise psychology, self-esteem has frequently attracted widespread attention among researchers. Similarly, as an effective way to reduce fatigue and relieve stress, physical activity has been always playing an important role in personal mental health. To date, several prior work has explored the potential relation between physical activity and self-esteem. Zhang puts forth that when teenagers faced with considerable academic pressure, their normal interpersonal relationships would be largely disturbed, but the physical activity can effectively alleviate this issue (Zhang, 2016). Simultaneously, actively engaging in physical activity can further enhance physical self-esteem level (Chen, 2012), and then the overall sense of wellbeing for college students could be obviously improved (Eather et al., 2016; Sun and Zhang, 2020). Moreover, several work has suggested that frequently participating in extracurricular exercise can effectively enhance self-esteem level (Yìğiter, 2014; Zhang et al., 2017); given that, as for college students, the higher self-esteem level they hold, the healthier mental health will be possessed by them (Xu et al., 2020). Additionally, in accordance with the exercise self-esteem model, physical activity could improve physical self-worth such as motor function, physical fitness, and physical condition, and then further enhance people's self-esteem (Sonstroem and Morgan, 1989). Based on those research mentioned above, it could be reasonably suggested that actively participating in physical activity could effectively improve the self-esteem among college students.

From these related literature review discussed above, it is not difficult to find that smartphone addiction caused by inappropriate or incorrect use of mobile phones would bring lots of passive effects to college students, and oppositely, as a positive and beneficial lifestyle, physical activity could effectively resolve this troublesome issue by indirectly improve individuals' self-esteem. In accordance with the interaction of person-affect-cognition-execution (I-PACE) model, addictive behavior such as smartphone addiction, is the result of a combination of triggering factors, mediators, and methods of execution (Brand et al., 2016; Li et al., 2022). Hence, it can be recognized that the low-level physical activity may be the triggering factors for smartphone addiction, and at the same time, that the improvement of self-esteem level by the enhancement of physical activity may play the mediating role in reducing the smartphone addiction. Given that, the present study hypothesized that physical activity would decrease smartphone addiction by indirectly improving self-esteem among college students; that is, self-esteem possibly mediates the relationship between physical activity and smartphone addiction.

2 Materials and methods

2.1 Procedures and participants

This study was carried out in accordance with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards, and also reviewed and approved by the Ethics Committee of South China University of Technology. This study used a cross-sectional survey to collect relevant data, and all of the data were gathered using several self-reported standard scales. The data collected in this study followed the principle of confidentiality, and all research subjects were totally voluntary. Before the formal survey, all participants gave written informed consent to us, at the same time, they were also informed to quit this survey at any time. Through the quota sampling, 650 college students were chosen from 10 colleges in Guangzhou Higher Mega Center, China, and 65 college students was conveniently selected from each college. If the participant usually communicates with other people by smartphone in daily life, and without any inborn diseases both from physical or mental aspects, he or she would be an eligible candidate to engage in this study. Among these, however, 42 samples were excluded due to incorrect or incomplete data, such as several missing or blank items in their answers, and he or she did not use smartphones in theirs daily life up till now, and even unfortunately someone had congenital motor dysfunction. Therefore, the final sample sizes in this study were 608, and the response rate of the questionnaire in the current article was 93.53%, which consists of 320 female (52.63%) and 288 male (47.37%) respondents. The sample included 317 (63.9%) liberal arts students and 291 (36.1%) science students. Furthermore, 253 college students (41.61%) were from rural area, and 355 participants (58.39%) from urban area, along with the average age of them was (20.27 ± 1.69) years.

2.2 Measures

2.2.1 Physical activity rating scale-3

Physical activity, was measured using the physical activity rating scale-3 (PARS-3) created originally by Liang and Liu (Liang and Liu, 1994), which includes three aspects, namely exercise duration, exercise frequency, and exercise intensity. The score range for each item is from 1 to 5, and the calculation formula of total score is intensity × (time-1) × frequency, with a range from 0 to 100. According to previous articles (Xia et al., 2018), the amount of physical activity can be divided into three levels from 1 (light exercise) to 3 (vigorous exercise): namely light exercise, moderate exercise and vigorous exercise. Light exercise is less than or equal to 19 points, moderate exercise is defined as 20 to 42 points, and equal to or more than 43 points would be classified as vigorous exercise. The Cronbach's α of PARS-3 in the current research was 0.693, which is basically satisfactory.

2.2.2 Self-esteem scale

Self-esteem, was measured using the self-esteem scale (SES) revised by Ji and Yu (1999) in order to objectively assess the overall self-esteem level of college students in China. The scale was compiled by Rosenberg (1965), and it was also a single dimensional scale consisting of ten items. The total score ranges from 4 to 40, and the higher score means the higher self-esteem level. Among them, items 3, 5, 8, 9, and 10 were reverse scoring questions. However, according to existing research (Tian, 2006; Shen and Cai, 2008; Wang et al., 2010), it was found that there were differences in cultural context when the scale was revised, so the item 8 would be conducted by a positive scoring manner in Chinese cultural context. And the SES has a good confidence level in this article, due to the Cronbach's α itself was 0.826.

2.2.3 Mobile phone addiction tendency scale

Smartphone addiction, was measured using the mobile phone addiction tendency scale (MPATS) developed by Xiong J. et al. (2012), which has been compiled based on Young's internet addiction scale (Young, 1998) and other relevant knowledge about the Internet addiction (Johansson and Götestam, 2004; Dowling and Quirk, 2009). It is a 5-point-Likert scale that includes 16 items and 4 dimensions: namely withdrawal symptom, salient behavior, social comfort, and mood change. The score for each item is from 0 (completely disagree) to 5 (completely agree), with the total score of 16 to 80 points. At the same time, higher score indicates a higher tendency addicted to mobile phones. The Cronbach's α of the MPATS in this study was 0.894, which presents a perfect reliability.

2.3 Statistical analysis

All data in the present study were calculated using SPSS 26.0 software. Continuous variables with normal distribution were displayed using mean (M) ± standard deviation (SD), while categorical variables were presented using frequencies and percentages. Firstly, the Harman's single-factor analysis method was used to ensure that the present research did not have obvious problem of common method variance. Secondly, the descriptive and correlation analysis were conducted to verify the relation between physical activity, self-esteem, and smartphone dependency. Thirdly, hierarchical regression analysis was used to test the predictive level of each variable on the dependent variable. Finally, model 4 from Process 4.0 in SPSS macro was utilized to analyze the mediating effect of self-esteem in the relationship between physical activity and smartphone dependency, and the bootstrapping method was also used to obtain 95% bias-corrected percentile confidence intervals (CI) generated by resampling data with 5,000 times (Hayes, 2013). The significance level of the this study was set at $P < 0.05$.

10.3389/fpsyg.2023.1256743

3 Results

3.1 Test for common method variance

The common method bias analysis was conducted through the Harman's single-factor test in the present study. In accordance with the final analysis result, there were 7 factors with the original root greater than 1, and the first common factor could explain 26.61% of the cumulative variance, which is less than the critical value with 40% required by the corresponding standard (Podsakoff et al., 2003; Xiong H. X. et al., 2012). Hence, there was no serious problem of common method bias in this research.

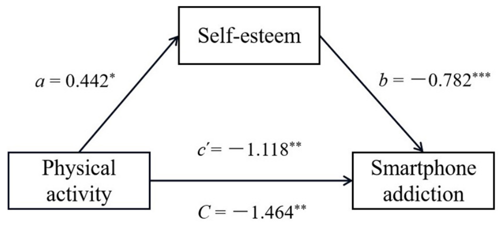


FIGURE 1
The path coefficient of mediating effect for self-esteem between physical activity and smartphone addiction. C = total effect; a, b, c' = direct effect; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

3.2 Descriptive statistics and correlation analysis

The results of descriptive statistics and correlation analysis were shown in Table 1. As is shown below, the average score of college students' physical activity amount was 17.61, which is located in the stage of the light-level exercise. Simultaneously, their self-reported score of smartphone addiction and self-esteem were all the moderate-level range, along with score of 42.81 and 28.52, respectively. In terms of correlation, physical activity was significantly and negatively correlated with smartphone addiction ($r = -0.124$, $p < 0.01$), but positively and significantly correlated with self-esteem ($r = 0.084$, $p < 0.05$). In addition, smartphone addiction was inversely associated with self-esteem ($r = -0.360$, $p < 0.01$).

3.3 Hierarchical regression analysis

Table 2 shows the hierarchical regression analysis of the demographic variables, physical activity, and self-esteem to predict the degree of smartphone addiction. As is shown below, gender, major, and source were put in Block 1, then physical activity was added to Block 2, and self-esteem followed in Block 3. In Model 1, gender was a positive factor in predicting smartphone addiction ($\beta = 0.089$, $p < 0.05$), explaining 2.2% of the variability of smartphone addiction. The physical activity negatively and significantly predicted smartphone addiction ($\beta = -1.00$, $p < 0.05$), accounting for 0.8% of the variance of smartphone addiction in Model 2. In the final Model 3, source could positively predict smartphone addiction and also reached a significant level ($\beta = 0.095$, $p < 0.05$), and self-esteem could negatively and significantly predict smartphone addiction ($\beta = -0.369$, $p < 0.001$), explaining 13.2% of the variability of smartphone addiction. In this table, the percentage of R^2 increased from 2.2 to 16.2%, and self-esteem could be a negative and significant predictor for smartphone addiction.

3.4 Mediating effect analysis

Table 3 shows the mediating effect of self-esteem between physical activity and smartphone addiction via stepwise regression analysis. Firstly, in the regression analysis of smartphone addiction on physical activity, physical activity was a negative predictor of smartphone addiction ($\beta = -0.131$, $p < 0.01$) and the model had a good fit [$F_{(1,606)} = 10.643$, $p < 0.01$]. At the same time, the 95% bootstrap confidence interval of the B excluded 0 and physical activity explained 1.7% of variance in smartphone addiction. In step 2, the regression analysis of self-esteem on physical activity revealed 0.8% of variance in self-esteem and the 95% bootstrap confidence interval excluded 0, which means physical activity could positively and significantly predict self-esteem ($\beta = 0.088$, $p < 0.01$). Likewise, this model also had an excellent fit [$F_{(1,606)} = 4.773$, $p < 0.05$]. Finally, the model of regression analysis for smartphone addiction on self-esteem and physical activity had a good fit [$F_{(2,605)} = 10.643$, $p < 0.001$] in step 3 and together explained 14% of the variance in smartphone addiction, along with both physical activity and self-esteem could negatively predict smartphone addiction ($\beta = -0.351$, $p < 0.001$; $\beta = -0.100$, $p < 0.01$). And as is clearly shown in Figure 1, self-esteem played a partial mediating role in the relationship between physical activity and smartphone addiction, and the indirect effect was −0.346 (95% Boot CI = −0.695; −0.023), which means physical activity could decrease smartphone addiction indirectly by improving self-esteem, and the mediating effect of self-esteem approximately accounted for 24% of the total effect.

4 Discussion

The present study was intended to disclose the underlying mediating mechanism between the relationship of physical activity and smartphone addiction, and ultimately found that physical activity could not only directly reduce smartphone addiction, but also indirectly decrease smartphone addiction by improving self-esteem. Taken this product into account, the hypothesis of the current study had been confirmed well. That is to say, self-esteem plays a mediating role between physical activity and smartphone addiction, and the mediating effect of self-esteem accounted for approximately 24% of the total effect between physical activity and smartphone addiction.

In recent years, as we all know, as an important research hotspot in the field of behavioral addiction and public health, smartphone addiction has increasingly attracted widespread attention for relevant researchers. Unreasonable or incorrect use of mobile phones not only leads to poor academic performance for college students (Hawi and Samaha, 2016), but will also

TABLE 1 Descriptive statistics and correlation analysis for main variables.

Variable	M	SD	Physical activity	Smartphone addiction	Self-esteem
Physical activity	17.61	5.61	–		
Smartphone addiction	42.81	10.63	−0.124**	–	
Self-esteem	28.52	4.77	0.084*	−0.360**	–

M, mean; SD, standard deviation; *$p < 0.05$; **$p < 0.01$.

TABLE 2 Hierarchical regression analysis of demographic indicators, physical activity, and self-esteem for smartphone addiction.

	Variable	Beta (β)	t	Δ R^2	Δ F	R^2	F
Model 1				0.022	4.427**	0.022	4.427**
Block 1	Sex	0.089	2.080*				
	Major	−0.075	−1.757				
	Source	0.042	1.021				
Model 2				0.008	5.224*	0.030	4.649**
Block 1	Sex	0.049	1.054				
	Major	−0.075	−1.753				
	Source	0.043	1.063				
Block 2	Physical activity	−1.00	−2.286*				
Model 3				0.132	94.526***	0.162	23.201***
Block 1	Sex	0.078	1.811				
	Major	−0.055	−1.388				
	Source	0.095	2.488*				
Block 2	Physical activity	−0.057	−1.385				
Block 3	Self-esteem	−0.369	−9.722***				

Beta (β), standardized coefficients; R^2, R square; ΔR^2, R square change; ΔF, F Change; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 3 The mediating effect analysis of self-esteem between physical activity and smartphone addiction.

	B(SE)	Beta (β)	t	95% CI	R	R^2	F
Step 1					0.131	0.017	10.643 **
Physical activity → smartphone addiction	−1.464 (0.449)	−0.131	−3.262**	−2.346, −0.582			
Step 2					0.088	0.008	4.773*
Physical activity → self-esteem	0.442 (0.202)	0.088	2.184*	0.044, 0.839			
Step 3					0.374	0.140	49.050***
Self-esteem → smartphone addiction	−0.783 (0.084)	−0.351	−9.272***	−0.948, −0.616			
Physical activity → smartphone addiction	−1.119 (0.422)	−0.100	−2.650**	−1.947, −0.289			

B, unstandardized coefficient; SE, standard error; Beta (β), standardized coefficient; 95% CI, 95% bootstrap confidence intervals; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

lead to several latent risks such as decreased life satisfaction and sleep quality (Visnjic et al., 2018), which ultimately results in severe physical and mental health problems or even the disease (Haug et al., 2015). Meanwhile, smartphone addiction could also bring a number of psychological pressures to college students (Jun, 2016; Wang et al., 2017; Ou-Yang et al., 2022; Kao, 2023). Therefore, how to efficiently decreasing smartphone addiction has become a huge and pressing challenge for us now. According to the results from the current work, physical activity could significantly and negatively predict smartphone addiction, which means the higher level of physical activity the college students hold, the lower trend they would be addicted to smartphones, which is consistent with preceding research (Yang et al., 2021, 2022). Simultaneously, the theory of temporal self-regulation of physical activity (Salmon, 2001; Chen et al., 2022) suggests that regularly participating in physical activity will be conducive to personal health. Given that, as a stress-relieving entertainment activity, physical activity is not only beneficial for improving the physical fitness of college students, but also an effective method to decrease smartphone addiction for them. Consequently, it can be easily seen that regularly participating in different kinds of physical activity would be greatly beneficial for college students to decrease the passive effects from smartphone addiction.

Consistent with the findings from previous research (Sung, 2014; He et al., 2019), the present study found a negative correlation between self-esteem and smartphone addiction, and self-esteem could inversely and significantly predict smartphone addiction, indicating that improving college students' self-esteem could effectively ameliorate their addiction to smartphones. In the light of the cognitive behavioral model about the Internet addiction, the non-adaptive cognitive and psychopathological factors of individuals can be viewed as the principal reasons for generating smartphone addiction, and the low-level self-esteem belongs to non-adaptive cognition (Davis, 2001). Quinones and Kakabadse (2015) revealed that individuals with low-level self-esteem could receive more positive evaluations and satisfying social experiences from others when engaging in online communication and other activities through their mobile phones. As we all know, as a virtual communication tool, Internet media might provide opportunities for those with low self-esteem to satisfy themselves and also shape themselves at the same time (Li et al., 2019), which inevitably makes them more dependent on using mobile phones for online communication to meet the demands they cannot achieve in the real life. Based on these mentioned above, it is not difficult to discover that college students with low self-esteem would be more likely to develop smartphone addiction, so the improvement of self-esteem would be an appropriate manner to solve this troublesome issue in coming days.

In addition, the present study also found that physical activity was significantly and positively correlated with the self-esteem. No doubt, as a feasible and effective exercise means, college students' self-efficacy and physical self-esteem could be enhanced via physical activity, and then their overall self-esteem could be naturally improved. At the same time, different exercise methods, exercise intensity, exercise duration, and exercise frequency all have beneficial effect on college students, especially for those with low-level self-esteem (Ye, 2007). According to the physical self-perception profile (Fox and Corbin, 1989), individuals' physical self-worth could be enhanced by the intervention with exercise, and then their athletic ability, physical condition, physical attractiveness, and strength would be also improved during that process, which ultimately leads to a remarkable increase in personal self-esteem. Furthermore, several scholars also proposed the notion that physical activity may improve individual's self-esteem level, and then their sense of happiness in life would be also increased in a large degree (Eather et al., 2016; Sun and Zhang, 2020). Therefore, it can be easily seen that college students actively participating in physical activity during their daily life could possess a higher self-esteem than those lack of physical exercise.

Last but not least, the main finding of the current study was that self-esteem mediated the relationship between physical activity and smartphone addiction, which means that physical activity could improve addictive college students' self-esteem and then indirectly decrease their smartphone addiction. According to the published research, people with lower self-esteem would be more likely to be dissatisfied with their lives compared to their counterparts (Hu et al., 2023), so that they usually attempt to compensate themselves by using electronic devices, especially the mobile phones, which would significantly increase the risk of smartphone addiction (Yang et al., 2004; He et al., 2020). However, a few previous studies have found that actively and regularly engaging in physical activity can not only alleviate academic pressure for college students (Zhang, 2016), but also get a healthier mentality (Xu et al., 2020), and such benefits as the improvement of personal self-esteem (Yiğiter, 2014; Zhang et al., 2017). Thus, personal smartphone addiction would be largely decreased, which mainly benefits from active participation in physical exercise in their daily lifestyle. According to the I-PACE model (Brand et al., 2016; Li et al., 2022), as a triggering factor for smartphone addiction, the lower level of physical activity will lead to the decrease of self-esteem, and then other abnormal methods would be used to compensate this deficiency for college students, such as using mobile phones to obtain personal satisfaction. And unfortunately, smartphone addiction would be finally hold by them. Based on these evidence above, it can reasonably draw a conclusion that self-esteem mediates the relationship between physical activity and smartphone addiction.

According to the pathway model for problematic use of the mobile phone summarized and suggested by Billieux (2012), he clearly points out that except for demographic variables, predictive factors in psychology for problematic mobile phone usage may contain two aspects, namely personality traits and its related psychological mechanisms, as well as self-esteem and its related psychological mechanisms, which means self-esteem would be an indispensable psychological variable to significantly predict individuals' smartphone dependency. And then, based on this model mentioned above and the update evidence about this issue, Billieux et al. (2015) put forward a comprehensive model for problematic mobile phone use again, and also conclude three potential paths to predict problematic mobile phone use; among them, the excessive reassurance path reveals that low self-esteem will be a vital risky factor to effectively predict problematic mobile phone use. Therefore, it can be easily seen that self-esteem can be viewed as an essential factor to predict smartphone addiction; that is, the lower self-esteem you will have, the deeper smartphone addiction you will possess. Undoubtedly, the result from the current work also fairly demonstrate this standpoint. However, how to effectively improve personal self-esteem level so as to prevent and even ameliorate smartphone addiction in daily life? Fortunately, Mcauley et al. (2000) conduct a randomized controlled trial to examine the relationship between physical activity and self-esteem in older adults, and finally disclose that the self-esteem level of them display considerable enhancement after different forms of exercise intervention with 6 months. In addition, apart from the elderly, a systematic reviews about exercise to improve self-esteem in children and young people aged from 3 to 20 years also reveal that physical exercise may has positive short-term effects on self-esteem in children and young people (Ekeland et al., 2005). Obviously, this finding is consistent with the result from this research, and more important, the present study also enhance the external validity of this result, namely physical exercise could improve individuals' self-esteem not only in children, young people, older adults, but also in college students aged over 20 years.

Nowadays, it is well known for us that as one of the most noticeable phenotype correlated with behavioral addictions all over the world, smartphone addiction has caused a large number of undesirable effects, as well as potential physical and mental harms to college students in daily life (Wang et al., 2017; Rathakrishnan et al., 2021; Ou-Yang et al., 2022; Kao, 2023). Therefore, how to properly deal with this puzzle by some efficient and reasonable manners has been put on agenda for relevant researchers, and it is fortunate that actively engaging and keeping in physical exercise would be a persuasive and practicable means to resolve this problem (Kim et al., 2015; Yang et al., 2019; Lin et al., 2022). Recently, a systematic review and meta-analysis presents that exercise would be an alternative approach for treating smartphone addiction, and this desirable intervention effect may be more significant in closed motor skills than in open motor skills, along with longer intervention duration may bring greater invention effects (Liu et al., 2019). Likewise, Kim (2013) also suggests that physical exercise would be beneficial to address this troublesome problem for people from both physiological and psychological aspects. And given that, the present research has explored the potential mediating mechanism between physical activity and smartphone addiction, and then also proved that self-esteem mediates the relationship between physical activity and smartphone addiction. Undoubtedly, this finding not only expands the related research in the field of behavioral addiction, but also serves as a feasible method for college students from China or even around the world to effectively resolve this troublesome issue in near future. That is to say, college students could not only indirectly improve their self-esteem by physical activity in daily life and then reduce their addiction to mobile phones, but also embrace this positive result through directly participating in various sorts of physical exercise.

5 Limitations

Despite those valuable implications discussed above, it is admittedly that there are also certain limitations existed in this study. Firstly, the present work conducted a cross-sectional survey research, thus the causal relationship can not be drawn by us. Secondly, the internal consistency coefficient of PARS-3 was only 0.693, and the reason is probably that this scale only has three items. Thirdly, the participants in this study were all from Guangzhou, which has limited the application and generalization of relevant results in some extent. Fourthly, even though self-esteem could mediate the relationship between smartphone dependency and physical activity, the indirect effect value seems somewhat small, and only accounting for 24% of the total effect. Given that, more related and potential variables need to be introduced to further explore the latent mediating role between physical activity and smartphone dependency. Fifthly, several advanced intelligent devices such as 3D-sensor pedometer and sports bracelet should be fully applied in near future, so that more accurate and reliable data could be naturally obtained by us, as well as more convincing and persuasive research consequences. In addition, it is necessary to mention that regarding assessment of duration with smartphone usage and personal subjective perception of its impact on individuals' daily lives should be also taken into account, which is highly pivotal for understanding and recognizing smartphone addiction to us. Last but not least, although this study revealed the association between physical activity and smartphone dependency can be mediated by self-esteem, but in near future, more cross-sectional or longitudinal research, and even the related experimental designs should be conducted to further prove the reliability and validity of this result from the present study.

6 Conclusion

The present study intends to examine the relationship among physical activity, self-esteem, and smartphone dependency, especially whether the self-esteem plays a mediating role between physical activity and smartphone dependency, and eventually concludes that self-esteem could mediate the relationship between physical activity and smartphone dependency, indicating that college students could improve their self-esteem through participating in physical activity, and then their trend toward smartphone dependency could be largely decreased. Consequently, it can be easily seen that this highly reliable and practicable way of actively engaging in physical activity would be a best choose for college students in China to effectively get rid of smartphone dependency and other similar issues about addictive behavior, and then also help them develop a healthy behavior in daily life in coming days. However, it is admittedly that this result from the current work should be further testified through other longitudinal or cross-sectional research, and even the experimental studies so as to demonstrate its validity and reliability once again.

Data availability statement

The original contributions presented in this study are included in this article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of South China University of Technology, and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. And the participants all provided their written informed consent before formally engaging in this study.

Author contributions

YK: Data curation, Formal analysis, Investigation, Writing – original draft. XL: Conceptualization, Formal analysis, Methodology, Validation, Writing – review & editing. XX: Data curation, Formal analysis, Investigation, Project administration, Writing – original draft. BH: Data curation, Formal analysis, Investigation, Writing – original draft. JW: Data curation, Formal analysis, Investigation, Writing – review & editing. LZ: Data curation, Formal analysis, Investigation, Validation, Writing – review & editing. HW: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – review & editing. GY: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Writing – review & editing.

Funding

The authors declare financial support was received for the research, authorship, and/or publication of this article. This research was funded by the Guangdong Office of Philosophy and Social Science Planning Project on Discipline Co-construction (No. GD22XTY01), the Project of Distinguished Young Talents in Higher Education of Guangdong (No. 2022WQNCX004), the Project of Guangzhou Municipal Science and Technology Bureau (No. 2023A04J1822), the Guangzhou Office of Philosophy and Social Science Planning Project (No. 2023GZGJ327), and also supported by the Fundamental Research Funds for the Central Universities (No. C2230470).

Acknowledgments

We thank all subjects who participated in the present study.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Baumeister, R. F., Campbell, J. D., Krueger, J. I., and Vohs, K. D. (2003). Does high self-esteem cause better performance, interpersonal success, happiness, or healthier lifestyles? *Psychol. Sci. Public Interest* 4, 1–44. doi: 10.1111/1529-1006.01431

Billieux, J. (2012). Problematic use of the mobile phone: A literature review and a pathways model. *Curr.Psychiatry Rev.* 8, 522–530. doi: 10.2174/157340012803520522

Billieux, J., Maurage, P., Lopez-Fernandze, O., Kuss, D. J., and Griffiths, M. D. (2015). Can disordered mobile phone use be considered a behavioral addiction? An update on current evidence and a comprehensive model for future research. *Curr. Addict. Rep.* 2, 156–162. doi: 10.1007/s40429-015-0054-y

Brand, M., Young, K. S., Laier, C., Wölfling, K., and Potenza, M. N. (2016). Integrating psychological and neurobiological considerations regarding the development and maintenance of specific Internet-use disorders: An interaction of person-affect-cognition-execution (I-PACE) model. *Neurosci. Biobehav. Rev.* 71, 252–266. doi: 10.1016/j.neubiorev.2016.08.033

Chen, F. F. (2012). Relationship between young children's physical self-esteem and their participation in sports. *J. ChengDu Sport Univ.* 38, 73–76. doi: 10.15942/j.jcsu.2012.10.013

Chen, H., Wang, C., Lu, T., Tao, B., Gao, Y., and Yan, J. (2022). The relationship between physical activity and college students' mobile phone addiction: The chain-based mediating role of psychological capital and social adaptation. *Int. J. Environ. Res. Public Health* 19, 9286–9295. doi: 10.3390/ijerph19159286

Choi, D. (2015). Physical activity level, sleep quality, attention control and self-regulated learning along to smartphone addiction among college students. *J. Korea Acad. Indust. Cooper. Soc.* 16, 429–437. doi: 10.5762/KAIS.2015.16.1.429

Davis, R. A. (2001). A cognitive-behavioral model of pathological Internet use. *Comput. Hum. Behav.* 17, 187–195. doi: 10.1016/S0747-5632(00)00041-8

Ding, Q., Wang, Z. Q., and Zhang, Y. G. (2020). Self-esteem and mobile phone addition: The serial mediating effect of fear of missing out and problematic social networking use. *Chin. J. Clin. Psychol.* 28, 1152–1156. doi: 10.16128/j.cnki.1005-3611.2020.06.015

Diotaiuti, P., Girelli, L., Mancone, S., Corrado, S., Valente, G., and Cavicchiolo, E. (2022a). Impulsivity and depressive brooding in internet addiction: A study with a sample of Italian adolescents during COVID-19 lockdown. *Front. Psychiatry* 13:941313. doi: 10.3389/fpsyt.2022.941313

Diotaiuti, P., Mancone, S., Corrado, S., Risio, A. D., Cavicchiolo, E., Girelli, L., et al. (2022b). Internet addiction in young adults: The role of impulsivity and codependency. *Front. Psychiatry* 13:893861. doi: 10.3389/fpsyt.2022.893861

Diotaiuti, P., Valente, G., and Mancone, S. (2021). Development and preliminary Italian validation of the emergency response and psychological adjustment scale. *Front. Psychol.* 12:687514. doi: 10.3389/fpsyg.2021.687514

Dowling, N. A., and Quirk, K. L. (2009). Screening for Internet dependence: Do the proposed diagnostic criteria differentiate normal from dependent Internet use? *Cyberpsychol. Behav.* 12, 21–27. doi: 10.1089/cpb.2008.0162

Eather, N., Morgan, P. J., and Lubans, D. R. (2016). Effects of exercise on mental health outcomes in adolescents: Findings from the CrossFit (TM) teens randomized controlled trial. *Psychol. Sport Exerc.* 26, 14–23. doi: 10.1016/j.psychsport.2016.05.008

Ekeland, E., Heian, F., Hagen, K. B., Abbott, J., and Nordheim, L. (2005). Exercise to improve self-esteem in children and young people. *Campbell Syst. Rev.* 1, 1–52. doi: 10.4073/csr.2005.4

Fox, K. R., and Corbin, C. B. (1989). The physical self-perception profile: Development and preliminary validation. *J. Sport Exer. Psychol.* 11, 408–430. doi: 10.1123/jsep.11.4.408

Gao, S., Zhang, X. K., and Xu, X. L. (2015). A meta-analysis of the relationship between self-esteem and mental health: The sample of Chinese college students. *Adv. Psychol. Sci.* 23, 1499–1508. doi: 10.3724/SP.J.1042.2015.01499

Gökçearslan, Ş., Mumcu, F. K., Haşlaman, T., and Çevik, Y. D. (2016). Modelling smartphone addiction: The role of smartphone usage, self-regulation, general self-efficacy and cyberloafing in university students. *Comput. Hum. Behav.* 63, 639–649. doi: 10.1016/j.chb.2016.05.091

Haug, S., Castro, R. P., Kwon, M., Filler, A., Kowatsch, T., and Schaub, M. P. (2015). Smartphone use and smartphone addiction among young people in Switzerland. *J. Behav. Addict.* 4, 299–307. doi: 10.1556/2006.4.2015.037

Hawi, N. S., and Samaha, M. (2016). To excel or not to excel: Strong evidence on the adverse effect of smartphone addiction on academic performance. *Comput. Educ.* 98, 81–89. doi: 10.1016/j.compedu.2016.03.007

Hayes, A. F. (2013). An introduction to mediation, moderation, and conditional process analysis: A regression-based approach. *J. Edu. Meas.* 3, 335–337. doi: 10.1111/jedm.12050

He, J., Li, S. S., and Fu, M. X. (2019). The relationship between mobile phone addiction and mental health, self-control and self-esteem in vocational students. *Chin. J. Sch. Health.* 40, 79–82. doi: 10.16835/j.cnki.1000-9817.2019.01.021

He, Q., Wang, Z. H., and Wang, M. L. (2020). The influence of adolescent interpersonal relational on the tendency of mobile phone addition: The chain mediating effect of self-esteem and anxiety. *Psychol. Res.* 13, 474–480.

Ho, F. K. W., Louie, L. H. T., Chow, C. B., and Wong, W. H. S. (2015). Physical activity improves mental health through resilience in Hong Kong Chinese adolescents. *BMC Pediatr.* 15:48. doi: 10.1186/s12887-015-0365-0

Hu, Y., Cai, Y., Wang, R., Gan, Y., and He, N. (2023). The relationship between self-esteem and aggressive behavior among Chinese adolescents: A moderated chain mediation model. *Front. Psychol.* 14:1191134. doi: 10.3389/fpsyg.2023.1191134

Ji, Y. F., and Yu, X. (1999). Self esteem scale. *Chin. J. Ment. Health* 13 (Suppl.), 318–320.

Johansson, A., and Götestam, K. G. (2004). Internet addiction: Characteristics of a questionnaire and prevalence in Norwegian youth (12–18 years). *Scand. J. Psychol.* 45, 223–229. doi: 10.1111/j.1467-9450.2004.00398.x

Jun, S. (2016). The reciprocal longitudinal relationships between mobile phone addiction and depressive symptoms among Korean adolescents. *Comput. Hum. Behav.* 58, 179–186. doi: 10.1016/j.chb.2015.12.061

Kao, P. C. (2023). The interrelationship of loneliness, smartphone addiction, sleep quality, and students' attention in English as a foreign language class. *Int. J. Environ. Res. Public Health* 20, 3460–3471. doi: 10.3390/ijerph20043460

Kim, H. (2013). Exercise rehabilitation for smartphone addiction. *J. Exer. Rehabil.* 9, 500–505. doi: 10.12965/jer.130080

Kim, H., and Kim, E. H. (2016). The relationship between anxious attachment and smartphone addiction: The mediating effects of loneliness and college adjustment. *Korea. J. Couns.* 17, 157–161. doi: 10.15703/kjc.17.2.201604.157

Kim, S. E., Kim, J. W., and Jee, Y. S. (2015). Relationship between smartphone addiction and physical activity in Chinese international students in Korea. *J. Behav. Addict.* 4, 200–205. doi: 10.1556/2006.4.2015.028

Li, F., Wang, Q. Y., Zhong, L. P., Zheng, X., and Wu, B. Y. (2019). Self-concept clarity and smartphone addiction among college students: The mediating effect of self-esteem and social anxiety. *Chin. J. Clin. Psychol.* 27, 900–904. doi: 10.16128/j.cnki.1005-3611.2019.05.009

Li, J., Lepp, A., and Barkley, J. E. (2015). Locus of control and cell phone use: Implications for sleep quality, academic performance, and subjective well-being. *Comput. Hum. Behav.* 52, 450–457. doi: 10.1016/j.chb.2015.06.021

Li, X., Li, W., Liu, M., Xiao, W., and Zhou, H. (2022). How does shyness affect Chinese college students' tendency to mobile phone addiction? Testing the mediating roles of social anxiety and self-control. *Front. Public Health* 10:902425. doi: 10.3389/fpubh.2022.902425

Liang, D. Q., and Liu, S. J. (1994). The relationship between stress level and physical exercise for college students. *Chin. Ment. Health J.* 8, 5–6.

Lin, B., Teo, E. W., and Yan, T. (2022). The impact of smartphone addiction on Chinese university students' physical activity: Exploring the role of motivation and self-efficacy. *Psychol. Res. Behav. Manag.* 31, 2273–2290. doi: 10.2147/PRBM.S375395

Liu, S., Xiao, T., Yang, L., and Loprinzi, P. D. (2019). Exercise as an alternative approach for treating smartphone addiction: A systematic review and meta-analysis of random controlled trials. *Int. J. Environ. Res. Public Health* 16, 3912–3927. doi: 10.3390/ijerph16203912

Liu, Z. H. (2020). Effects of physical exercise on negative emotion for university students—The mediating and moderating effects of self-efficacy and mental resilience. *J. Phys. Educ.* 27, 102–108. doi: 10.16237/j.cnki.cn44-1404/g8.2020.05.014

Mcauley, E., Blissmer, B., Katula, J., and Mihalko, D. S. L. (2000). Physical activity, self-esteem, and self-efficacy relationships in older adults: A randomized controlled trial. *Ann. Behav. Med.* 22, 131–145. doi: 10.1007/bf02895777

Ou-Yang, Q., Liu, Q., Song, P. Y., Wang, J. W., and Yang, S. (2022). The association between academic achievement, psychological distress, and smartphone addiction: A cross-sectional study among medical students. *Psychol. Health Med.* 27, 1–14. doi: 10.1080/13548506.2022.2148697

Podsakoff, P. M., MacKenzie, S. B., Lee, J. Y., and Podsakoff, N. P. (2003). Common method biases in behavioral research: A critical review of the literature and recommended remedies. *J. Applied Psychol.* 5, 879–903. doi: 10.1037/0021-9010.88.5.879

Quinones, C., and Kakabadse, N. K. (2015). Self-concept clarity and compulsive internet use: The role of preference for virtual interactions and employment status in British and North-American samples. *J. Behav. Addict.* 4, 289–298. doi: 10.1556/2006.4.2015.038

Rathakrishnan, B., Singh, S. S. B., Kamaluddin, M. R., Yahaya, A., Mohd-Nasir, M. A., Ibrahim, F., et al. (2021). Smartphone addiction and sleep quality on academic performance of university students: An exploratory research. *Int. J. Environ. Res. Public Health* 18, 8291–8300. doi: 10.3390/ijerph18168291

Rosenberg, M. (1965). *The measurement of self-esteem, society and the adolescent self-image*. Princeton, NJ: Princeton Press.

Salmon, P. (2001). Effects of physical exercise on anxiety, depression, and sensitivity to stress: A unifying theory. *Clin. Psychol. Rev.* 21, 33–61. doi: 10.1016/S0272-7358(99)00032-X

Shen, Z. L., and Cai, T. S. (2008). Processing of item 8 of the Chinese version of the self-esteem scale. *Chin. J Ment. Health* 22, 661–663.

Sohn, S. Y., Rees, P., Wildridge, B., Kalk, N. J., and Carter, B. (2019). Prevalence of problematic smartphone usage and associated mental health outcomes amongst children and young people: A systematic review, meta-analysis and grade of the evidence. *BMC Psych.* 19:356. doi: 10.1186/s12888-019-2350-x

Sonstroem, R. J., and Morgan, W. P. (1989). Exercise and self-esteem: Rationale and model. *Med. Sci. Sport Exer.* 21, 329–337. doi: 10.1249/00005768-198906000-00018

Sun, C., and Zhang, G. L. (2020). The impact of physical activity on adolescents' interpersonal competence: A chain mediating model. *Chin. J. Sport Med.* 39, 47–52. doi: 10.16038/j.1000-6710.2020.01.009

Sung, E. J. (2014). A study on the effects of parenting method on selfesteem and school life adaptation: With mobile phone dependency as parameter. *J. Policy Dev.* 14, 107–130. doi: 10.35224/kapd.2014.14.1.005

Tang, J. J., Hao, J. H., Han, H., Wan, Y. H., Li, H. Y., Gu, X., et al. (2016). Relationship between mobile phone dependence and injury among Bengbu middle school students. *Chin. J. Sch. Health.* 37, 208–211. doi: 10.16835/j.cnki.1000-9817.2016.02.015

Tian, L. M. (2006). The Chinese version of the Rosenberg self-esteem scale and its shortcomings. *Psychol. Explor.* 26, 88–91.

Visnjic, A., Velickovic, V., Sokolovic, D., Stankovic, M., Mijatovic, K., Stojanovic, M., et al. (2018). Relationship between the manner of mobile phone use and depression, anxiety, and stress in university students. *Int. J. Environ. Res. Public Health* 15, 697–705. doi: 10.3390/ijerph15040697

Wang, M. C., Cai, B. G., Wu, Y., and Dai, X. Y. (2010). The impact of project presentation methods on the factor structure of the Chinese Rosenberg self-esteem scale. *Psychol. Explor.* 30, 63–65.

Wang, P., Zhao, M., Wang, X., Xie, X., Wang, Y., and Lei, L. (2017). Peer relationship and adolescent smartphone addiction: The mediating role of self-esteem and the moderating role of the need to belong. *J. Behav. Addict.* 6, 708–717. doi: 10.1556/2006.6.2017.079

Xia, X. W., Huang, J. L., and Liu, D. (2018). Investigation and study of university graduate students' physical exercise behavior affecting factors. *J. Phys. Educ.* 25, 102–108. doi: 10.16237/j.cnki.cn44-1404/g8.2018.05.010

Xiong, H. X., Zhang, J., Ye, B. J., Zheng, X., and Sun, P. Z. (2012). Common method variance effects and the models of statistical approaches for controlling it. *Adv. Psychol. Sci.* 20, 757–769. doi: 10.3724/SP.J.1042.2012.00757

Xiong, J., Zhou, Z. K., Chen, W., You, Z. Q., and Zhai, Z. Y. (2012). Development of the mobile phone addiction tendency scale for college students. *Chin. Ment. Health* 26, 222–225.

Xu, H. Z., Gao, L., Xiao, L., and Wang, C. Y. (2020). An experimental study on the influence of baduanjin exercise on "weak" college students' physical self-esteem and exercise motivation. *J. Chengdu Sport Univ.* 46, 102–108. doi: 10.15942/j.jcsu.2020.05.016

Yang, F. Y., Zhang, F. J., and Jiang, Q. D. (2004). Research on self-esteem and related factors of problem students. *J. Psychol. Sci.* 27, 615–619. doi: 10.16719/j.cnki.1671-6981.2004.03.024

Yang, G., Li, Y. X., Liu, S. J., Liu, C. N., Chen, J., and Wang, S. T. (2021). Physical activity influences the mobile phone addiction among Chinese undergraduates: The moderating effect of exercise type. *J. Behav. Addict.* 10, 799–810. doi: 10.1556/2006.2021.00059

Yang, G., Shangguan, R., Ke, Y., and Wang, S. T. (2022). The influence of acute aerobic exercise on craving degree for university students with mobile phone dependency: A randomized controlled trial. *Int. J. Environ. Res. Public Health* 19, 8983–8991. doi: 10.3390/ijerph19158983

Yang, G., Tan, G. X., Li, Y. X., Liu, H. Y., and Wang, S. T. (2019). Physical exercise decreases the mobile phone dependence of university students in China: The mediating role of self-control. *Int. J. Environ. Res. Public Health.* 16, 4098–4109. doi: 10.3390/ijerph16214098

Ye, D. H. (2007). A review of the research on physical training and physical self-esteem of college students. *Zhejiang Sport Sci.* 139, 110–113.

Yìğiter, K. (2014). The effects of participation in regular exercise on self-esteem and hopelessness of female university students. *Soc. Behav. Personal.* 42, 1233–1244. doi: 10.2224/sbp.2014.42.8.1233

Young, K. S. (1998). Internet addiction: The emergence of a new clinical disorder. *Cyber Psychol. Behav.* 1, 237–244. doi: 10.1089/cpb.1998.1.237

Zeidan, J., Hallit, S., Akel, M., Louragli, I., and Obeid, S. (2021). Problematic smartphone use and affective temperaments among Lebanese young adults: Scale validation and mediating role of self-esteem. *BMC Psychol.* 9:136. doi: 10.1186/s40359-021-00638-y

Zhang, G. L., Qiu, Y., and Cao, M. (2017). The relationship between physical activities and external problem behaviors of adolescents: The mediating effect of self-esteem. *Chin. J. Sport Med.* 36, 521–525. doi: 10.16038/j.1000-6710.2017.06.009

Zhang, M. (2016). Research on the influence of education and exercise on improving the physical health and interpersonal relationships of adolescents. *J. Nanjing Sport Inst.* 30, 88–94. doi: 10.15877/j.cnki.nsic.2016.05.016

frontiers | Frontiers in Sports and Active Living

TYPE Original Research
PUBLISHED 05 April 2024
DOI 10.3389/fspor.2024.1360145

OPEN ACCESS

EDITED BY
María Rodriguez-Ayllon,
Erasmus Medical Center, Netherlands

REVIEWED BY
Antonio Cicchella,
University of Bologna, Italy
Irene Monzonís-Carda,
University of Jaume I, Spain

*CORRESPONDENCE
Migle Baceviciene
✉ migle.baceviciene@lsu.lt

†These authors have contributed equally to this work and share first authorship

RECEIVED 22 December 2023
ACCEPTED 25 March 2024
PUBLISHED 05 April 2024

CITATION
Jankauskiene R and Baceviciene M (2024) Mindful monitoring and accepting the body in physical activity mediates the associations between physical activity and positive body image in a sample of young physically active adults.
Front. Sports Act. Living 6:1360145.
doi: 10.3389/fspor.2024.1360145

Mindful monitoring and accepting the body in physical activity mediates the associations between physical activity and positive body image in a sample of young physically active adults

Rasa Jankauskiene[1†] and Migle Baceviciene[2*†]

[1]Institute of Sport Science and Innovations, Lithuanian Sports University, Kaunas, Lithuania,
[2]Department of Physical and Social Education, Lithuanian Sports University, Kaunas, Lithuania

Introduction: The study aimed to extend research on the possible mechanisms that explain the associations between physical activity (PA), mindfulness during PA and positive body image. In the present study, we tested the mediating role of state mindfulness during PA in the association between PA and trait body appreciation. We also explored the moderating roles of sex and body mass index (BMI) in these associations.
Methods: In total, 759 students participated in the study but after applying the inclusion criteria 539 questionnaires were approved for analysis, with a mean age of 23.3 ± 7.2 years (49.7% were women). Study participants completed the online survey, which included sociodemographic details, PA data, the State Mindfulness Scale for Physical Activity 2 (SMS-PA-2) and the Body Appreciation Scale 2 (BAS-2).
Results: Monitoring and accepting the body during exercise mediated the association between PA and body appreciation. BMI moderated the association between accepting the body during exercise and body appreciation: for heavier individuals with BMI > 24.99 kg/m^2, the associations between accepting the body during exercise and body appreciation were higher ($B = 0.53$, $p < 0.001$) compared to those whose body weight was in the normal range ($B = 0.21$, $p < 0.001$).
Conclusion: Strengthening mindfulness and promoting mindful body acceptance during exercise might enhance a positive body image, especially in individuals with a higher BMI.

KEYWORDS
state mindfulness, physical activity, Monitor and Acceptance Theory (MAT), positive body image, embodiment

1 Introduction

Mindfulness is described as self-regulation of attention, awareness, monitoring and accepting the mind and body and the reduction of cognitive and emotional reactivity (1, 2). Mindfulness might be conceptualized as both a reliable individual difference (dispositional or trait mindfulness) and as a momentary experience that can vary within individuals across time and context (state mindfulness) (3). Weak to moderate correlations were observed in associations between trait mindfulness and more frequent PA (4). However, there is less research on testing the relationships between PA and state mindfulness.

The mechanisms through which trait mindfulness is related to PA are based on improved self-control through increased attention and acceptance, improved self-regulation, increased satisfaction and more autonomous motivation (5–10). Attention and acceptance, as cognitive characteristics, might have the ability to override or inhibit unhealthy habits. Specifically, mindful awareness of PA could enhance the acceptance of negative and uncomfortable thoughts and sensations that might occur during PA, especially in novice exercisers, individuals with body image concerns and the overweight (i.e., shame, discomfort, pain, fatigue, exertion). Increased self-control, improved attention and awareness leading to higher self-regulation, greater satisfaction and more autonomous exercise motivation might help to encourage people to sustain PA in both the short and long term.

Systematic studies revealed that positive body image is related to higher PA and greater body functionality appreciation (11–13). Possible pathways that explain increased positive body image as an outcome of participation in PA include increased objective and subjective physical fitness, self-efficacy (increased empowerment and feeling of competence and control), lower body surveillance and self-objectification and an increase in body functionality appreciation (14–17). Research show that PA positively affects body image only in the case of autonomous motivation (18). Mechanisms through which PA positively affects body image are not yet fully understood since most of the studies are atheoretical (11).

Some PAs are considered to be more mindful compared to other activities. For example, yoga was considered mindfulness-based PA because it focuses on mindful-based movements, mindful breathing, focused attention to the body, contains mindful components by being process-oriented and emphasizes body and mind connection (19). Results of previous studies suggested that mindfulness-based PAs such as yoga might have an enhancing effect on positive body image and physical self-perception (15, 17, 20–23). Important prospective study demonstrated that yoga participation decreased self-objectification (treating self as an object to be viewed and evaluated based on appearance) and increased self-concept, internal reasons for exercise (health and fitness) and state mindfulness during PA (20).

However, despite the evidence that some PAs are more mindful, it is reasonable to assume that all PA might be associated with higher general mindfulness compared to a sedentary lifestyle. Physical inactivity and a sedentary lifestyle might be seen as practices that neglect and ignore the authentic needs of the body. PA and sports are contexts in which the body has a central focus of an individual's lived experience and it is an ideal way to experience it (14). A professionally prescribed and delivered PA might increase concentration, strength, stamina and coordination and give rise to an internally oriented experience of the body through more frequent states of mind–body integration and positive embodiment (16).

Based on the Developmental Theory of Embodiment (24) and/or the Embodiment Model of Positive Body Image (14, 16), embodiment is an internally oriented state of mind–body connection in which one experiences one's body as an essential aspect of interrelated experiences of competence, relatedness to others, power, self-expression, vitality and well-being. It places a person more in tune with the body's sensations and more appreciative of body functions (24). Positive embodiment is in contrast to the self-objectification, body surveillance and societal focus on appearance that is associated with dysfunctional eating and exercise (25). In highly body image-concerned individuals, health-damaging PA patterns beyond the normal frequency and intensity are observed, including exercising for permission to eat, exercising in the absence of proper nutrition/hydration and exercising when injured and feeling pain, exercising for self-punishment or harm (26). In other words, in dysfunctional exercise individuals demonstrate low levels of body awareness, ignore their feelings and thoughts or neglect body needs.

In mindfulness, the internal aspects of the self (i.e., feelings, thoughts, physiological needs) are well represented (1). In mindful PA, physical movements are implemented with attention, purpose, self-compassion, acceptance, awareness and joy. Mindful PA is focused on the process of becoming more connected, healthier and stronger, whereas mindless exercise is often appearance-based and focused on outcomes (26–28). In PA, people might demonstrate different levels of monitoring, awareness and acceptance of their feelings, thoughts and physical sensations of the body, thus possessing different levels of mindfulness (4, 29). Mindful awareness and acceptance in PA means that individuals are aware and accept the inner aspects of the self (body, thoughts and feelings) in a non-judgmental way.

Recently, the Monitor and Acceptance Theory (MAT) was developed (30). This theory postulates that mindfulness includes two components of attention monitoring and acceptance, which together might explain its impact on psychological well-being. Attention monitoring skills enhance the awareness of present-moment internal and external experiences and affect positive cognitive outcomes, affective experience and reactivity. Acceptance skills modify the way one relates to the present-moment experience, regulating reactivity to affective experience (30, 31). MAT is an important theory that might help to explain the role of mindfulness in PA and its correlates (32). Open and non-judgmental awareness (monitoring) of physical body sensations during PA might support feelings of confidence in the body, as well as general feelings of competence and autonomy.

Novice exercisers, overweight individuals and persons with body image concerns might feel discomfort in PA and thus body and mind monitoring skills might help them to regulate the intensity of PA or the content of exercises fostering feelings of autonomy, competence and self-control. Acceptance of negative or uncomfortable thoughts or body sensations (i.e., body shame, fatigue, pain, exertion, etc.) during PA might help novice exercisers and individuals with body image concerns to sustain PA both in the short and long term (4). Mindful PA and positive body image might be connected in reciprocal and self-perpetuating ways. For example, mindful PA might increase positive feelings about one's own body and these positive feelings might increase PA. Thus, it is important to understand the role of mindfulness in the associations between PA in general and positive body image. This knowledge might inform PA, positive body image promotion-focused interventions as well as prevention and treatment programmes for individuals which body weight is higher than normal range.

There are no data reporting significant sex differences in mindfulness during PA. However, men and people with body mass index (BMI) of normal ranges report higher positive body image and less body dissatisfaction compared to women and those which body weight is higher than normal ranges (33–35). It is explained by different sociocultural expectations for sexes and stronger pressures to attain appearance ideals for women compared to men and for people with different than stereotyped body images (36). Also, PA in men is higher compared to women, especially in young adult age (37). Therefore, sex and BMI might moderate the associations between PA, mindfulness, and positive body image. No previous studies tested moderating role of sex and BMI in the associations between PA, mindfulness during PA and positive body image.

Based on previous studies, the present study aims to extend research on the possible mechanisms that explain the associations between PA, mindfulness and positive body image. Specifically, the aim of the present study was to test the mediating role of mindful monitoring and acceptance of mind and body during PA in the associations between PA and positive body image (operating as body appreciation, Figure 1). In the present study, we expect that mindfulness (monitoring and accepting body and mind) during PA will mediate the associations between PA and positive body image. The second aim was to test the moderating role of sex and BMI in the associations between the variables of the model. We hypothesized that the associations between PA, mindfulness and positive body image might be stronger in women compared to men and in people with the higher BMI compared to those which BMI is in normal ranges.

2 Materials and methods

2.1 Participants and procedures

The study was approved by the Social Research Ethics Board of the Lithuanian Sports University (Protocol No. SMTEK-131) and data were collected between November 2022 and May 2023. Study participants of the present study were technical, medical, health, social sciences and humanities students at Lithuanian universities and colleges. First, permission to implement the survey was obtained from tadministrative units of the universities and colleges. The non-probabilistic sampling method was used to recruit the students, with 759 meeting the inclusion criteria and thus participating in the survey. Only 539 questionnaires were confirmed for further analysis after applying the inclusion criteria (age ≥ 18 years, studying at university or college, Lithuanian language spoken, regular participation in any sport for no less than six months and participation in an exercise session no longer than two weeks ago). Students who confirmed not exercising, exercising for less than six months and not being able to recall their experience during the last exercise session were excluded from this study ($n = 220$). The mean age of the students was 23.3 ± 7.2 years (range: 18–44 years).

The online survey was implemented using the SurveyMonkey platform and a trained researcher distributed the link to the study participants. All questions were set as mandatory; thus, no missing data were observed. Only one response from the same IP address was accepted. After introducing the study aims, information about anonymity of the questionnaire and the approximate time needed for completing the questionnaire, students provided digital informed consent and were directed to the Measures section. The Measures section of the questionnaire included questions assessing positive body image, PA, state mindfulness in PA and BMI. Students who refused to participate or did not meet the inclusion criteria were eliminated from the study. Students could end participation in the study at any point simply by closing their browser; in that case, their answers were not recorded.

2.2 Measures

The participants reported their sex, age, university, programme of studies and the nature of their PA (home exercise, recreational, organized individual sports, organized team sports). Furthermore, students were asked to report the time of their last exercise session.

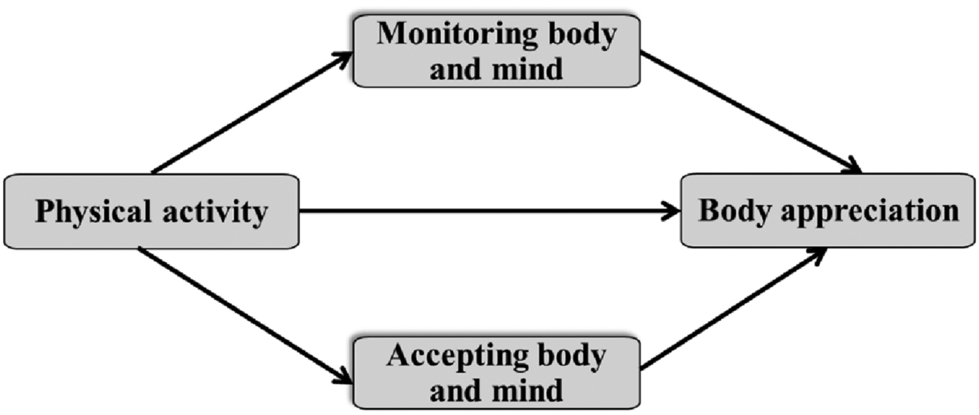


FIGURE 1
Hypothetical model of the study.

State mindfulness during PA was assessed using the Lithuanian version of the State Mindfulness in Physical Activity Scale 2 (SMS-PA-2; 29). The 19-item instrument consists of four subscales: Monitoring Mind (6 items), Monitoring Body (6 items), Accepting Mind (3 items) and Accepting Body (4 items) in PA. Examples of items are: Monitoring Mind, "I noticed pleasant and unpleasant thoughts"; Monitoring Body, "I was aware of how my body felt"; Accepting Mind, "I let my thoughts/emotions just be without judging them"; and Accepting Body, "I accepted how my body felt even if it was unpleasant". The scale uses a five-point Likert scale with responses ranging from "not at all" (1) to "very much" (5). The higher scores show the greater monitoring and/or accepting body and/or mind. The final score is calculated by averaging the response options for each subscale of the SMS-PA-2 and the total scale, thus it can vary in the range from 1 to 5. The Lithuanian version of the manuscript demonstrated acceptable psychometric properties (38). In the present sample, internal consistency was good, with Cronbach's alpha values of 0.87 for the general instrument, 0.83 for Monitoring Mind, 0.86 for Monitoring Body, 0.63 for Accepting Mind and 0.76 for Accepting Body.

PA was assessed using the Lithuanian version of the Leisure-Time Exercise Questionnaire (LTEQ; 39). The participants of the study reported the frequency of light, moderate and strenuous PA that lasted for no less than 15 min during the previous week. The frequency of light PA was multiplied by 3, moderate activity by 5 and strenuous activity by 9. The scores of each type of PA were summed to obtain the total PA score, with higher scores representing higher PA. The Lithuanian version of the instrument was applied previously for testing young adults (40).

Positive body image was assessed using the Lithuanian version of the Body Appreciation Scale 2 (BAS-2; 41). This scale is one-dimensional and consists of 10 items. Examples of the items are: "I respect my body" and "I appreciate the different and unique characteristics of my body". The answers are scored on a Likert scale from 1 (*Never*) to 5 (*Always*) and then summed and averaged, with higher scores indicating higher body appreciation. The psychometric properties of the Lithuanian version of the questionnaire were good (42). Furthermore, the instrument demonstrated good scalar invariance across 65 nations (43). In the present study, Cronbach's alpha for the scale was good ($\alpha = 0.95$).

The BMI was calculated using self-reported body weight (kg) and height (m): Weight/(Height)^2. In the student sample, the BMI ranged from 14.9 to 38.0 (mean = 23.1, SD = 3.3) kg/m^2. The criteria for classification of study participants into underweight (<18.5 kg/m^2; 4.6%), normal weight (18.5–24.9 kg/m^2; 71.8%), overweight (25.0–29.9 kg/m^2; 20.4%) and obesity (≥30.0 kg/m^2; 3.2%) categories were suggested by the World Health Organization (44).

2.3 Statistical analyses

Preliminary analyses, correlation analyses and testing of the variables' distribution normality and internal consistency of the scales were conducted using SPSS v.29 (IBM Corp., Armonk, NY, USA). A Cronbach's alpha value of >0.65 was considered to be adequate (45) but it should be noted that Cronbach's alpha values are sensitive to the number of items included in the scale (46). After confirming the distribution normality of all the continuous variables, Pearson's correlation coefficient was used to test the associations between study variables. Correlations of 0.1–0.3 were considered to be small, those of >0.3 and <0.5 as moderate and those of ≥0.5 as strong, with a significance level of <0.05 (47).

In addition, moderated mediation analysis was conducted using Mplus v.7.8 (Muthen & Muthen, Los Angeles, CA, USA). The calculated power for this sample ($n = 539$) was 0.98 for the model with Accepting Body and Monitoring Body as the two parallel mediators during exercise and 0.24–0.30 for the model with Accepting Mind and Monitoring Mind (48). PA was used as the independent variable (X), mindfulness in monitoring and accepting the body and mind during exercise as parallel mediators (M1, M2) and body appreciation as the dependent variable (Y). Finally, a moderating role of sex (male and female) and BMI groups (normal weight and overweight/obesity) was tested on all the paths of the mediation model: from X to M1 and M2, from M1 and M2 to Y and the directly from X to Y.

A bootstrapping procedure was used to test the significance of the total and indirect effects and the differences in these effects across levels of the moderator variables with 5,000 bootstrap samples (49). The 95% confidence intervals for the coefficients calculated by bootstrapping methods were considered statistically significant if the confidence intervals did not include 0.

3 Results

Five hundred thirty-nine ($n = 539$) individuals participated in study. From them 268 (49.7%) were women. Most of the sample comprised university students (90.2%) engaged in first-degree studies (86.8%) and having BMI in normal range (71.8%). All study participants were engaged in sports, with around half of them in recreational activities (50.5%). Other half of the sample (49.5%) participated in individual and/or organized team sports. Half of the study sample (50.2%) reported participation in sports on the same day as completing the survey or the day before, 26.3% two or three days before, 9.3% within one week, 14.2% within two weeks.

Pearson's correlation coefficients between study measures are presented in Table 1. A higher level of PA was positively and weakly correlated with the Monitoring Mind, Monitoring Body and Accepting Body subscales and body appreciation. Stronger associations were found between the body monitoring and acceptance and body appreciation ($r = 0.43$) than with the monitoring and accepting mind subscales ($r = 0.16$ and 0.21). Correlations between different SMS-PA-2 subscales demonstrated medium to strong correlations (0.29–0.56).

In Figure 2, a mediated model of PA, mindfulness in monitoring and accepting the body during exercise and body appreciation is presented. Mindfulness in monitoring and accepting the body served as parallel mediators in the association

TABLE 1 Correlations between physical activity, state mindfulness in monitoring and accepting the mind and body and body appreciation ($n = 539$).

Study measures	BMI	PA	MM	AM	MB	AB	BA
Body mass index (BMI)	1.00						
Physical activity (PA)	−0.01	1.00					
Monitoring mind (MM)	−0.05	0.09*	1.00				
Accepting mind (AM)	0.05	0.06	0.32**	1.00			
Monitoring body (MB)	−0.03	0.18**	0.38**	0.29**	1.00		
Accepting body (AB)	−0.01	0.18**	0.32**	0.42**	0.56**	1.00	
Body appreciation (BA)	−0.12**	0.18**	0.16**	0.21**	0.43**	0.43**	1.00

*$p < 0.05$.
**$p < 0.01$; body appreciation was measured by the body appreciation scale 2; monitoring mind, accepting mind, monitoring body, and accepting body are subscales from the state mindfulness scale in physical activity 2.

between PA and body appreciation. Also, a direct association between PA and body appreciation was found. All information on direct, indirect and total effects is presented in Figure 2 footnotes. In addition, PA and monitoring and accepting the body during exercise explained 24% of the variance in body appreciation.

In the next step, we tested the moderated roles of sex and BMI on all the paths explored previously. There were no sex moderating roles on any path: from physical activity to monitoring the body during exercise ($\beta = 0.17$, $p = 0.175$), from physical activity to accepting the body ($\beta = 0.25$, $p = 0.051$), from monitoring the body to body appreciation ($\beta = -0.31$, $p = 0.209$), from accepting the body to body appreciation ($\beta = 0.02$, $p = 0.942$) and directly from physical activity to body appreciation ($\beta = -0.13$, $p = 0.316$).

No moderating roles of BMI were found between physical activity and both study mediators: accepting the body ($\beta = 0.05$, $p = 0.696$) and monitoring the body ($\beta = -0.14$, $p = 0.291$) during the exercise. Also, BMI did not moderate the direct association between monitoring the body during exercise and body appreciation ($\beta = -0.37$, $p = 0.087$). Importantly, BMI moderated the association ($\beta = 0.61$, $p = 0.002$) between accepting the body during the last exercise session and body appreciation (Figure 3). It was revealed that for overweight students, the association between accepting the body during the last exercise session and body appreciation was stronger ($B = 0.53$, $p < 0.001$) than for those with a normal BMI of <25.0 kg/m^2 ($B = 0.21$, $p < 0.001$). Lastly, the direct association between physical activity and body appreciation was also moderated by the BMI ($\beta = 0.26$, $p = 0.040$): the association between physical activity and body appreciation was not significant for study subjects with normal BMI ($B = 0.001$, $p = 0.351$), but was significant for overweight ($B = 0.01$, $p = 0.004$).

In the last step, a mediated model of PA, mindfulness in monitoring and accepting the mind during PA and body appreciation was tested. Due to weak correlations between the study variables, the calculated power for this model was inadequate (0.24–0.30) and the association between PA and accepting and monitoring the mind during exercise was not

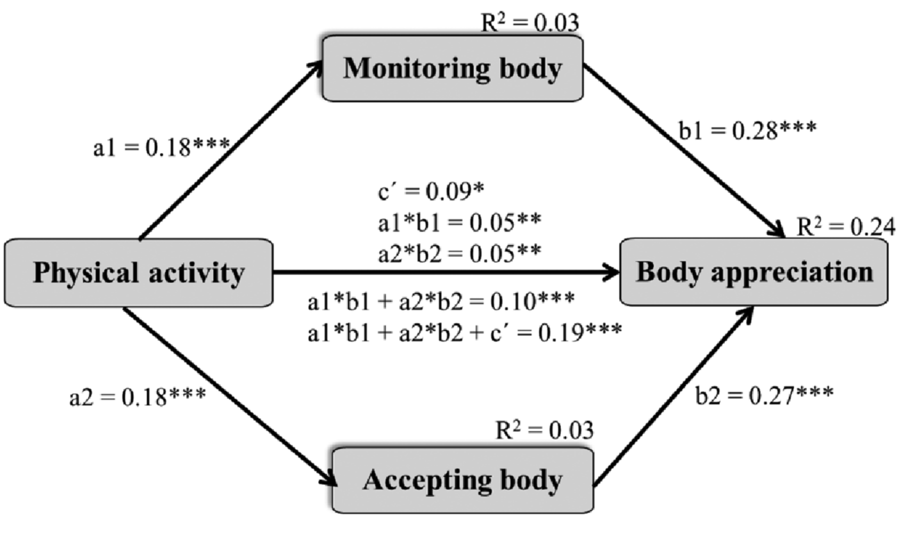


FIGURE 2
Mediated model of physical activity, mindfulness in monitoring and accepting the body during exercise and body appreciation. * $p < 0.05$, **$p < 0.01$, *** $p < 0.001$ two-tailed; coefficients are standardised; a1—effect from the independent variable (X) on mediator 1 (M1), b1—effect from M1 on the dependent variable (Y), a2—effect from X on M2, b2—effect from M2 on Y, ć—direct effect from X to Y, a1*b1—specific indirect effect of X on Y via M1 only, a2*b2—specific indirect effect of X on Y via M2 only, a1*b1 + a2*b2—total indirect effect of X on Y via M1, M2, a1*b1 + a2*b2 + ć—total effect.

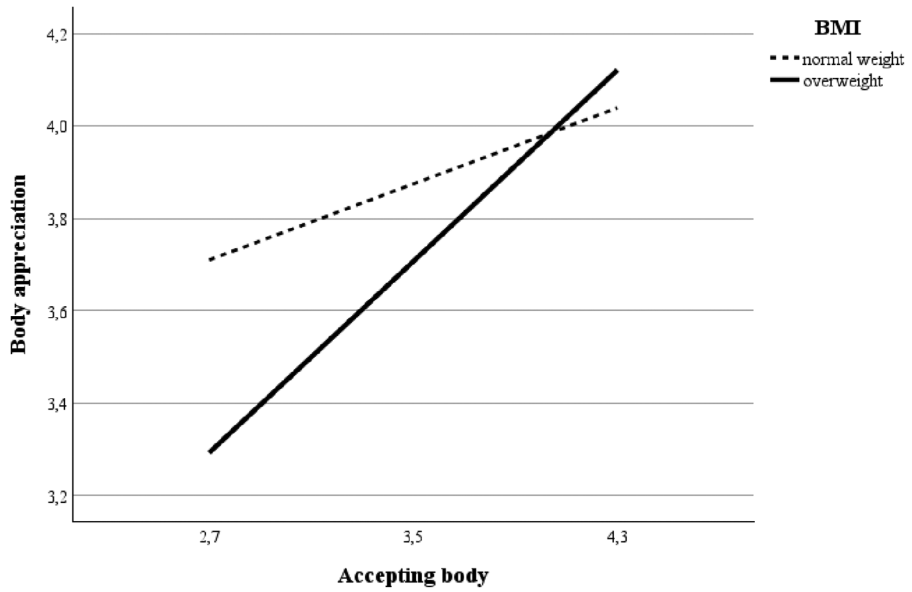


FIGURE 3
Moderating role of body mass index (BMI) on the association between accepting the body during the last exercise session and body appreciation.

significant. The desired level of power is 0.80 or 80% probability of finding a significant result. Thus, accepting and monitoring the mind during the exercise did not mediate the path between PA and body appreciation (Figure 4). There was a direct association between PA and body appreciation and the associations between monitoring and accepting the mind during exercise and body appreciation were also significant. All information on direct, indirect and total effects is presented in Figure 4 footnotes. PA and monitoring and accepting the mind during exercise explained only 7% of the variance in body appreciation.

As the model demonstrated poor statistical power and no significant mediating roles of monitoring and accepting the mind during the last exercise in the association between physical activity and body appreciation, the moderating roles of sex and BMI were not additionally tested.

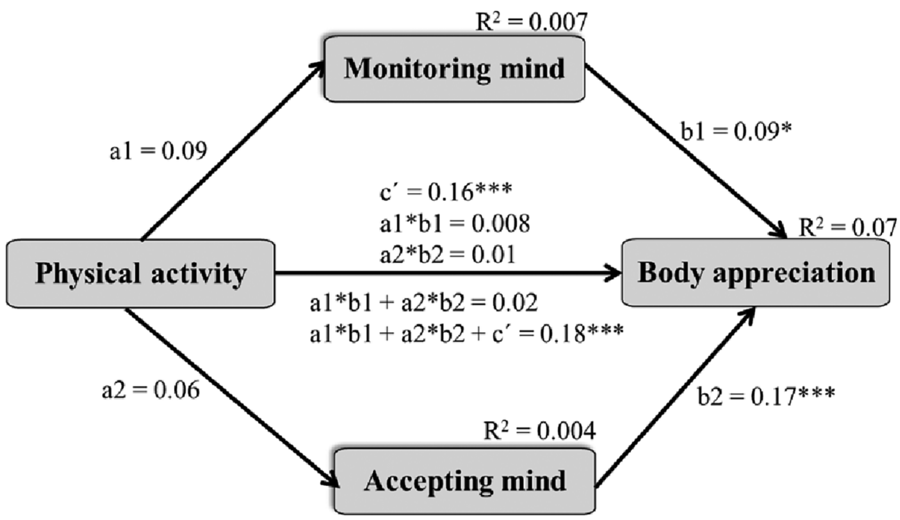


FIGURE 4
Mediated model of physical activity, mindfulness in monitoring and accepting the mind during exercise and body appreciation. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ two-tailed; coefficients are standardised; a1—effect from the independent variable (X) on mediator 1 (M1), b1—effect from M1 on the dependent variable (Y), a2—effect from X on M2, b2—effect from M2 on Y, ć—direct effect from X to Y, a1*b1—specific indirect effect of X on Y via M1 only, a2*b2—specific indirect effect of X on Y via M2 only, a1*b1 + a2*b2—total indirect effect of X on Y via M1, M2, a1*b1 + a2*b2 + ć—total effect.

4 Discussion

The present study expands the knowledge of the possible mechanisms that explain the associations between PA, mindfulness and positive body image. Overall, the present results provided evidence that body-related mindfulness (monitoring and accepting the body) during PA is an important mediator between PA and body appreciation in physically active young adults of both sexes. Below we highlight how the results of the present study uniquely add to the literature assessing the relationships between PA, mindfulness and positive body image.

4.1 Mediating role of monitoring and accepting the body and mind in associations between physical activity and body appreciation

The results of the present study suggest and add important new knowledge indicating that participation in PA is associated with body appreciation not only directly but also through the two mediators of monitoring and accepting the body. This finding is in line with the Monitoring and Acceptance Theory (MAT), which postulated that attention monitoring skills enhance awareness of the present moment and affect positive cognitive outcomes, affective experience and reactivity and acceptance skills, all of which modify the way one relates to the present-moment experience, thus regulating reactivity to affective experience (30, 31). Specifically, our study adds important new knowledge that open and non-judgmental awareness (monitoring) and acceptance of physical body sensations during PA are associated with enhanced body appreciation. This new knowledge might inform PA and positive body image promotion-focused interventions, as well as prevention and treatment programmes for individuals with higher body image concerns (25, 50). Previous studies show that body image concerns and insecurity about the body are related to lower PA and the avoidance of PA (11, 12). Thus, increasing mindfulness in PA might enhance non-judgmental monitoring and acceptance of the body, which further increases a positive body image.

Previous studies showed that mindfulness-based physical activities such as yoga increase a positive body image (15, 17, 21, 22, 50). The present study adds important new knowledge that various physical activities might be beneficial to the body image of exercising young adults if body-related mindfulness (non-judgmental monitoring and acceptance of the body) is increased. It is important to acknowledge that the SMS-PA-2 did not let us assess the connections between body and mind, which is the central construct of embodiment (14, 16, 24). Based on the Embodiment Model of Positive Body Image (14, 16), embodying physical activities increases a positive body image through mediators such as embodiment (awareness and attentiveness to the body, a sense of physical empowerment, increased body and mind integration) and lower self-objectification (understanding and treating your body as an object) (14). Thus, increased embodiment or enhanced body and mind connection might be another important mediators through which PA, mindfulness and positive body image might be interrelated in young exercising adults (14, 24). In future studies we recommend testing mindfulness in PA using instruments that allow the connection between mind and body to be assessed (16).

In the present study, we observed no mediating role of monitoring and accepting the mind in the associations between PA and body appreciation. We also observed lower correlations between monitoring and accepting the mind and body appreciation than between monitoring and accepting the body and body appreciation. An explanation for these results might be that monitoring and accepting the mind in PA has lower or minimal significance for body appreciation. PA and sports are contexts in which the body has a central focus; and monitoring and accepting the mind are more distal variables to the body compared to monitoring and accepting the body in PA contexts. Furthermore, young and physically active adults participated in the present study. It might be that people who exercise feel less mental and/or psychological discomfort during PA because of their higher adaptation to PA and increased interoceptive awareness (afferent sensing, central processing and mental representation of the internal body signals) compared to the sedentary population (51). Therefore, it is important to investigate samples with lower PA or those not constantly exercising in future studies. However, because this study is one of the first to test the associations between general PA, mindfulness during exercise and body appreciation, our findings could be random. We therefore recommend that future studies test this model of PA and body appreciation on different samples.

4.2 Moderating role of sex and body weight in the associations between physical activity, mindful body acceptance and body appreciation

In the present study, we also tested the moderating role of sex and BMI in the associations of the model. No moderating role of sex were observed, suggesting that the associations between PA and mindfulness and monitoring and associations between acceptance of the body with body appreciation are similar in both sexes. The sample of the present study consisted of young physically active adults and physical activity, body appreciation as well as interoceptive awareness in women of our sample might be higher compared to women from the sedentary populations (11). It is possible that we did not observe differences for women and men because of the ceiling effect. Nevertheless, it is one of the first studies, and future research should be continued to have more knowledge on this topic.

However, our study showed that the associations between body acceptance during PA and body appreciation are stronger in overweight and obese participants than in participants of normal body weight. This is important new knowledge showing that mindfulness in PA, especially body acceptance, might be more beneficial for positive body image development in overweight and obese people compared to individuals with normal body weight. Overweight individuals report higher negative body image and/or body image concerns and less positive body image (34, 52, 53), therefore they more often experience negative body sensations during PA (i.e., body shame, fatigue, pain, exertion). These negative body-related feelings might prevent them from PA or even promote resistance to it (54). Thus, the results of the present study show that enhancing mindfulness in PA, especially acceptance of the body, might help individuals with higher BMI and/or body image concerns to develop a more positive body image and to sustain PA (4).

Importantly, no moderating role of body weight were observed in testing other associations of the hypothetical model. For example, BMI was not a moderator in the associations between monitoring of the body and body appreciation. This is an important finding suggesting that mindful acceptance, but not mindful monitoring, of the body is an important variable for the development of positive body image in individuals with higher body mass. These results inform intervention programmes for obesity prevention and treatment and might suggest that for individuals with higher body image concerns, mindful acceptance of the body should be emphasized during PA.

4.3 Practical implications

The findings of the present study might inform PA, positive body image promotion-focused interventions and prevention and treatment programmes for overweight individuals. Including mindfulness training in sports and PA practices, as well as teaching sport and health and fitness coaches to implement strategies enhancing mindfulness, might help exercisers to develop more healthy attitudes towards their body image. These findings also might inform obesity treatment interventions, suggesting that integration of sports practices that include mindful monitoring and acceptance of the body might help individuals with higher body weight to develop a positive body image as an outcome of physical exercise. Positive body image is related to more mindful eating and lower body weight (55–57), therefore these programmes might also help overweight individuals to decrease excessive body weight more effectively compared to general PA programmes in which mindfulness is ignored.

4.4 Limitations and strengths of the present study

The main limitation of the present study is its cross-sectional design, which did not allow us to understand the directions of the associations between the study variables. It might be that individuals with a more positive body image demonstrate higher mindful body monitoring and acceptance skills and therefore are more physically active. Another limitation is that we did not assess the duration of previous sports participation in the present study. A longer sports experience might be an important moderator that changes the strength of the associations between PA, mindfulness during exercise and positive body image. In other words, in longer exercising individuals the associations between monitoring and acceptance of the body and body appreciation might be higher compared to novice exercisers. We recommend testing this assumption in future studies.

Another limitation was that state mindfulness was not assessed immediately after the exercise session but some time later, asking participants to recall the last exercise session. Half of the exercisers reported that they exercised on that or the previous day; however, 14% of the sample recalled that the last workout was more than a week ago. This is an important limitation and in future studies we recommend that state mindfulness be assessed immediately after the exercise session, as recommended by the authors of the SMS-PA-2 (29). We also recommend assessing satisfaction with body, body functionality appreciation, enjoyment of PA and interoceptive awareness in future studies. These variables might be important for testing the associations between PA, mindfulness and positive body image (17, 51, 58–60).

The main strength of the present study was that we tested the associations between state mindfulness and PA. Previous systematic research reported a large gap in the literature on this topic (3). Another strength is that we assessed state mindfulness in a sample of young adults practicing various sports, including organized individual and team sports, recreational exercise and exercising at home. Previous studies tested the role of mindfulness for body image in small specific samples of exercisers (i.e., yoga). In contrast to studies assessing only one type of sport, testing the sample participating in various sports let us to see a general and complex picture of the mediating role of mindfulness in the associations between PA and positive body image. A further strength of the study was that we explored a sample of physically active individuals that included both sexes. Finally, an important strength of the present study is that we used internationally sound measures such as the BAS-2 and SMS-PA2.

5 Conclusions

The results of the present study show that mindful monitoring and acceptance of the body during PA mediate the associations between PA and positive body image (operating as body appreciation) in a sample of young physically active adults. Monitoring and accepting the mind did not mediate these associations. The associations between mindful acceptance of the body and positive body image were stronger in individuals with higher body mass compared to those with a normal body mass index. These findings might inform positive body image promotion programmes suggesting that using coaching methods that increase mindful monitoring and acceptance of the body during exercise might help to develop a healthier body image in exercisers and enhance more inclusive exercise environments in the sports and recreational exercise sectors.

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.

Ethics statement

The studies involving humans were approved by Social Research Ethics Board of the Lithuanian Sports University (Protocol No. SMTEK-131). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RJ: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. MB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article.

This study was funded by the Research Council of Lithuania (Grant. No. S-MIP-22-25).

Acknowledgments

The authors wish to thank Vaiva Balciuniene for her contribution to data collection.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2024.1360145/full#supplementary-material

References

1. Kabat-Zinn J. *Wherever You Go, There You Are: Mindfulness Meditation in Everyday Life*. UK: Hachette (2009).

2. Kabat-Zinn J. *Full Catastrophe Living, Revised Edition: How to Cope with Stress, Pain and Illness Using Mindfulness Meditation*. UK: Hachette (2013).

3. Yang C-H, Conroy DE. Mindfulness and physical activity: a systematic review and hierarchical model of mindfulness. *Int J Sport Exerc Psychol*. (2020) 18(6):794–817. doi: 10.1080/1612197X.2019.1611901

4. Schneider J, Malinowski P, Watson PM, Lattimore P. The role of mindfulness in physical activity: a systematic review. *Obes Rev*. (2019) 20(3):448–63. doi: 10.1111/obr.12795

5. Deci EL, Ryan RM. *Handbook of Self-Determination Research*. Rochester, NY: University Rochester Press (2004).

6. Bandura A. The primacy of self-regulation in health promotion. *App Psychol Int Rev*. (2005) 54(2):245–54. doi: 10.1111/j.1464-0597.2005.00208.x

7. Brown KW, Ryan RM, Creswell JD. Mindfulness: theoretical foundations and evidence for its salutary effects. *Psychol Inq*. (2007) 18(4):211–37. doi: 10.1080/10478400701598298

8. Tsafou KE, De Ridder DT, van Ee R, Lacroix JP. Mindfulness and satisfaction in physical activity: a cross-sectional study in the Dutch population. *J Health Psychol*. (2016) 21(9):1817–27. doi: 10.1177/1359105314567207

9. Tsafou KE, Lacroix JP, van Ee R, Vinkers CD, De Ridder DT. The relation of trait and state mindfulness with satisfaction and physical activity: a cross-sectional study in 305 Dutch participants. *J Health Psychol*. (2017) 22(10):1221–32. doi: 10.1177/1359105315624748

10. Cox AE, Ullrich-French S, Austin B. Testing the role of state mindfulness in facilitating autonomous physical activity motivation. *Mindfulness*. (2020) 11 (4):1018–27. doi: 10.1007/s12671-020-01311-y

11. Sabiston CM, Pila E, Vani M, Thogersen-Ntoumani C. Body image, physical activity, and sport: a scoping review. *Psychol Sport Exerc*. (2019) 42:48–57. doi: 10.1016/j.psychsport.2018.12.010

12. Vani M, Murray R, Sabiston C. Body image and physical activity. In: Zenko Z, Jones L, editors. *Essentials of Exercise and Sport Psychology: An Open Access Textbook*. Society for Transparency, Openness, and Replication in Kinesiology (2021). p. 150–75. doi: 10.51224/B1007

13. Linardon J, Messer M, Tylka TL. Functionality appreciation and its correlates: systematic review and meta-analysis. *Body Image*. (2023) 45:65–72. doi: 10.1016/j.bodyim.2023.02.002

14. Menzel JE, Levine MP. Embodying experiences and the promotion of positive body image: the example of competitive athletics. In: Calogero RM, Tantleff-Dunn S, Thompson JK, editors. *Self-Objectification in Women: Causes, Consequences, and Counteractions*. Washington, DC, US: American Psychological Association (2011). p. 163–86. doi: 10.1037/12304-008

15. Mahlo L, Tiggemann M. Yoga and positive body image: a test of the embodiment model. *Body Image*. (2016) 18:135–42. doi: 10.1016/j.bodyim.2016.06.008

16. Menzel JE, Thompson JK, Levine MP. *Development and Validation of the Physical Activity Body Experiences Questionnaire*. Guilford (2019). doi: 10.1521/bumc.2019.83.1.53

17. Alleva JM, Tylka TL, van Oorsouw K, Montanaro E, Perey I, Bolle C, et al. The effects of yoga on functionality appreciation and additional facets of positive body image. *Body Image*. (2020) 34:184–95. doi: 10.1016/j.bodyim.2020.06.003

18. Panão I, Carraça EV. Effects of exercise motivations on body image and eating habits/behaviours: a systematic review. *Nutr Diet*. (2020) 77(1):41–59. doi: 10.1111/1747-0080.12575

19. La Forge R. Aligning mind and body: exploring the disciplines of mindful exercise. *ACSM's Health Fitness J*. (2005) 9(5):7. doi: 10.1097/00135124-200509000-00006

20. Cox AE, Ullrich-French S, Cole AN, D'Hondt-Taylor M. The role of state mindfulness during yoga in predicting self-objectification and reasons for exercise. *Psychol Sport Exerc*. (2016) 22:321–7. doi: 10.1016/j.psychsport.2015.10.001

21. Cox AE, Ullrich-French S, Howe HS, Cole AN. A pilot yoga physical education curriculum to promote positive body image. *Body Image*. (2017) 23:1–8. doi: 10.1016/j.bodyim.2017.07.007

22. Halliwell E, Dawson K, Burkey S. A randomized experimental evaluation of a yoga-based body image intervention. *Body Image*. (2019) 28:119–27. doi: 10.1016/j.bodyim.2018.12.005

23. Cox AE, Tylka TL. A conceptual model describing mechanisms for how yoga practice may support positive embodiment. *Eat Disord*. (2020) 28(4):376–99. doi: 10.1080/10640266.2020.1740911

24. Piran N, Teall TL, Counsell A. The experience of embodiment scale: development and psychometric evaluation. *Body Image*. (2020) 34:117–34. doi: 10.1016/j.bodyim.2020.05.007

25. Cook-Cottone CP. Incorporating positive body image into the treatment of eating disorders: a model for attunement and mindful self-care. *Body Image*. (2015) 14:158–67. doi: 10.1016/j.bodyim.2015.03.004

26. Calogero RM, Pedrotty-Stump KN. Chapter 25—incorporating exercise into eating disorder treatment and recovery: cultivating a mindful approach. In: Maine M, McGilley BH, Bunnell DW, editors. *Treatment of Eating Disorders*. San Diego: Academic Press (2010). p. 425–41. doi: 10.1016/B978-0-12-375668-8.10025-7

27. Loumidis K, Wells A. Exercising for the wrong reasons: relationships among eating disorder beliefs, dysfunctional exercise beliefs and coping. *Clin Psychol Psychother*. (2001) 8(6):416–23. doi: 10.1002/cpp.298

28. Piran N. *Handbook of Positive Body Image and Embodiment: Constructs, Protective Factors, and Interventions*. New York, NY: Oxford University Press (2019).

29. Ullrich-French S, Cox AE, Huong C. The state mindfulness scale for physical activity 2: expanding the assessment of monitoring and acceptance. *Meas Phys Educ Exerc Sci*. (2022) 26(2):116–29. doi: 10.1080/1091367X.2021.1952207

30. Lindsay EK, Creswell JD. Mechanisms of mindfulness training: monitor and acceptance theory (MAT). *Clin Psychol Rev*. (2017) 51:48–59. doi: 10.1016/j.cpr.2016.10.011

31. Simione L, Saldarini F. A critical review of the monitor and acceptance theory of mindfulness. *Mindfulness*. (2023) 14(6):1317–28. doi: 10.1007/s12671-023-02129-0

32. Cox AE, Ullrich-French S, French BF. Validity evidence for the state mindfulness scale for physical activity. *Meas Phys Educ Exerc Sci*. (2016) 20(1):38–49. doi: 10.1080/1091367X.2015.1089404

33. Weinberger NA, Kersting A, Riedel-Heller SG, Luck-Sikorski C. Body dissatisfaction in individuals with obesity compared to normal-weight individuals: a systematic review and meta-analysis. *Obes Facts*. (2016) 9(6):424–41. doi: 10.1159/000454837

34. He J, Sun S, Lin Z, Fan X. The association between body appreciation and body mass index among males and females: a meta-analysis. *Body Image*. (2020) 34:10–26. doi: 10.1016/j.bodyim.2020.03.006

35. He J, Sun S, Zickgraf H, Lin Z, Fan X. Meta-analysis of gender differences in body appreciation. *Body Image*. (2020) 33:90–100. doi: 10.1016/j.bodyim.2020.02.011

36. Fredrickson BL, Roberts T-A. Objectification theory: toward understanding women's lived experiences and mental health risks. *Psychol Women Q*. (1997) 21(2):173–206. doi: 10.1111/j.1471-6402.1997.tb00108.x

37. Engberg E, Alen M, Kukkonen-Harjula K, Peltonen JE, Tikkanen HO, Pekkarinen H. Life events and change in leisure time physical activity. *Sports Med*. (2012) 42(5):433–47. doi: 10.2165/11597610-000000000-00000

38. Baceviciene M, Jankauskiene R, Balciuniene V. Mindfulness, physical activity and sports participation: validity evidence of the Lithuanian translation of the state mindfulness scale for physical activity 2 in physically active young adults. *Behav Sci*. (2023) 13(10):820. doi: 10.3390/bs13100820

39. Godin G. The godin-shephard leisure-time physical activity questionnaire. *Health Fitness J Canada*. (2011) 4(1):18–22. doi: 10.14288/hfjc.v4i1.82

40. Baceviciene M, Jankauskiene R. Changes in sociocultural attitudes towards appearance, body image, eating attitudes and behaviours, physical activity, and quality of life in students before and during COVID-19 lockdown. *Appetite*. (2021) 166:105452. doi: 10.1016/j.appet.2021.105452

41. Tylka TL, Wood-Barcalow NL. The body appreciation scale-2: item refinement and psychometric evaluation. *Body Image*. (2015) 12:53–67. doi: 10.1016/j.bodyim.2014.09.006

42. Baceviciene M, Jankauskiene R. Associations between body appreciation and disordered eating in a large sample of adolescents. *Nutrients*. (2020) 12(3):752. doi: 10.3390/nu12030752

43. Swami V, Tran US, Stieger S, Aavik T, Ranjbar HA, Adebayo SO. Body appreciation around the world: measurement invariance of the body appreciation scale-2 (BAS-2) across 65 nations, 40 languages, gender identities, and age. *Body Image*. (2023) 46:449–66. doi: 10.1016/j.bodyim.2023.07.010

44. Word Health Organization. *Obesity: Preventing and Managing the Global Epidemic: Report of a WHO Consultation on Obesity*. Geneva, Switzerland: WHO (1997). Available online at: https://iris.paho.org/handle/10665.2/43000 (accessed November 8, 2023).

45. Vaske JJ, Beaman J, Sponarski CC. Rethinking internal consistency in Cronbach's alpha. *Leis Sci*. (2017) 39(2):163–73. doi: 10.1080/01490400.2015.1127189

46. Taber KS. The use of Cronbach's alpha when developing and reporting research instruments in science education. *Res Sci Educ*. (2018) 48(6):1273–96. doi: 10.1007/s11165-016-9602-2

47. Cohen J. *A Power Primer*. 4th ed. Washington, DC, US: American Psychological Association (Methodological Issues and Strategies in Clinical Research (2016). p. 284. doi: 10.1037/14805-018

48. Schoemann AM, Boulton AJ, Short SD. Determining power and sample size for simple and complex mediation models. *Soc Psychol Personal Sci*. (2017) 8(4):379–86. doi: 10.1177/1948550617715068

49. Rockwood NJ, Hayes AF. Mediation, moderation, and conditional process analysis: regression-based approaches for clinical research. In: Wright AGC, Hallquist MN, editors. *The Cambridge Handbook of Research Methods in Clinical Psychology*. Cambridge: Cambridge University Press (Cambridge Handbooks in Psychology) (2020). p. 396–414. doi: 10.1017/9781316995808.037

50. Borden A, Cook-Cottone C. Yoga and eating disorder prevention and treatment: a comprehensive review and meta-analysis. *Eat Disord*. (2020) 28(4):400–37. doi: 10.1080/10640266.2020.1798172

51. Wallman-Jones A, Perakakis P, Tsakiris M, Schmidt M. Physical activity and interoceptive processing: theoretical considerations for future research. *Int J Psychophysiol*. (2021) 166:38–49. doi: 10.1016/j.ijpsycho.2021.05.002

52. Annis NM, Cash TF, Hrabosky JI. Body image and psychosocial differences among stable average weight, currently overweight, and formerly overweight women: the role of stigmatizing experiences. *Body Image*. (2004) 1(2):155–67. doi: 10.1016/j.bodyim.2003.12.001

53. Paans NPG, Bot M, Brouwer IA, Visser M, Penninx BWJH. Contributions of depression and body mass index to body image. *J Psychiatr Res*. (2018) 103:18–25. doi: 10.1016/j.jpsychires.2018.05.003

54. Lucibello KM, Sabiston CM, O'Loughlin EK, O'Loughlin LO. Mediating role of body-related shame and guilt in the relationship between weight perceptions and lifestyle behaviours. *Obes Sci Pract*. (2020) 6(4):365–72. doi: 10.1002/osp4.415

55. Avalos LC, Tylka TL. Exploring a model of intuitive eating with college women. *J Couns Psychol*. (2006) 53(4):486–97. doi: 10.1037/0022-0167.53.4.486

56. Tylka TL, Wood-Barcalow NL. What is and what is not positive body image? Conceptual foundations and construct definition. *Body Image*. (2015) 14:118–29. doi: 10.1016/j.bodyim.2015.04.001

57. Linardon J, Messen M, Tylka TL. Body appreciation and its psychological correlates: a systematic review and meta-analysis. *Body Image*. (2022) 42:287–96. doi: 10.1016/j.bodyim.2022.07.003

58. Cox AE, Roberts MA, Cates HL. Mindfulness and affective responses to treadmill walking in individuals with low intrinsic motivation to exercise. *Int J Exerc Sci*. (2018) 11(5):609–24. PMID: 29541336; PMCID: PMC5841682.

59. Kerner C, Kirk D, De Meester A, Haerens L. Why is physical education more stimulating for pupils who are more satisfied with their own body? *Health Educ J*. (2019) 78(3):251–65. doi: 10.1177/0017896918798420

60. Todd J, Aspell JE, Barron D, Swami V. Multiple dimensions of interoceptive awareness are associated with facets of body image in British adults. *Body Image*. (2019) 29:6–16. doi: 10.1016/j.bodyim.2019.02.003

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 16 May 2024
DOI 10.3389/fpsyg.2024.1376961

Check for updates

OPEN ACCESS

EDITED BY
María Rodriguez-Ayllon,
Erasmus Medical Center, Netherlands

REVIEWED BY
Aurelio Olmedilla,
University of Murcia, Spain
Tomas Vencurik,
Masaryk University, Czechia
Wendy E. Huddleston,
University of Wisconsin–Milwaukee,
United States

*CORRESPONDENCE
Iker Madinabeitia
✉ ikermadi@ugr.es

RECEIVED 26 January 2024
ACCEPTED 29 April 2024
PUBLISHED 16 May 2024

CITATION
Gutiérrez-Capote A, Madinabeitia I, Alarcón F, Torre E, Jiménez-Martínez J and Cárdenas D (2024) Acute effect of complexity in basketball on cognitive capacity. *Front. Psychol.* 15:1376961. doi: 10.3389/fpsyg.2024.1376961

Acute effect of complexity in basketball on cognitive capacity

Alejandro Gutiérrez-Capote[1,2], Iker Madinabeitia[1,2,3]*, Francisco Alarcón[3], Elisa Torre[1,2], Jesús Jiménez-Martínez[1,2] and David Cárdenas[1,2]

[1]Department of Physical Education and Sport, Faculty of Sports Science, University of Granada, Granada, Spain, [2]Sport and Health University Research Institute (iMUDS), Granada, Spain, [3]Department of General and Specific Didactics, Faculty of Education, University of Alicante, Alicante, Spain

Background: Executive functions, notably inhibition, significantly influence decision-making and behavioral regulation in team sports. However, more research must be conducted on individual player characteristics such as experience and motor skills. This study assessed how accumulated practical experience moderates inhibition in response to varying task difficulty levels.

Methods: Forty-four university students (age: 20.36 ± 3.13 years) participated in this study with two sessions: one followed standard 1×1 basketball rules ("Regular Practice"), while the other imposed motor, temporal, and spatial restrictions ("Restriction Practice"). Functional difficulty was controlled by grouping pairs with similar skill levels. Flanker and Go-Nogo tasks were used.

Results: Increasing complexity worsened cognitive performance (inhibition). "Restriction Practice" showed a significantly slower and less accurate performance in both tests than "Regular Practice" ($p < 0.001$). Experience positively impacted test speed and accuracy ($p < 0.001$).

Conclusion: In sports, acute cognitive impacts are intrinsically linked to the task's complexity and the athlete's cognitive resources. In this sense, it is essential to adjust individually the cognitive demands of the tasks, considering each athlete's specific cognitive abilities and capacities.

KEYWORDS

executive function, inhibitory control, restriction, cognitive load, training, basketball

1 Introduction

In the broad range of definitions related to higher cognition, executive functions are identified as a group of capacities crucial for conscious and directed behavior control toward achieving specific goals (Diamond, 2013). These functions are essential for overcoming cognitive challenges in sports environments by facilitating the coordination between thought and action to achieve adaptive goals (Bravi et al., 2022). The study of the interaction between sports practice and cognitive functions promises not only to identify and enhance athletic talent (Scharfen and Memmert, 2019), but also to evaluate specific sports as potential interventions to enhance cognitive abilities in individuals with cognitive impairments, benefiting both young people and older adults (Tsai, 2009).

The inhibitory component of executive functions involves the ability to selectively concentrate on achieving a goal while ignoring distracting stimuli (Miyake et al., 2000). This component is particularly relevant in the sports domain (Liao et al., 2017), especially in interaction sports characterized by high levels of uncertainty (Swann et al., 2015), where it is crucial to control emotions and impulses. Recent research suggests that inhibition processes should be considered a set of functions rather than a single construct. Despite the various classifications proposed for the different inhibitory abilities, there is a consensus on distinguishing two main types: interference control "or perceptual inhibition" and response inhibition. The main difference between the two is that they address different manifestations of inhibitory responding: executing the response in the face of distractor stimuli (Flanker task) or not initiating any response -impulse control- (Go-Nogo) (Xie et al., 2017). Although many authors also include cognitive inhibition, such as the suppression of previously active rules in working memory in order to focus on new rules and apply them effectively, several psychometric studies suggest that this ability to change can be considered a distinct executive function (Miyake et al., 2000).

Evidence of a bidirectional interaction between inhibitory control (IC) and physical exercise (PE) exists. Most recent interventional studies (the only ones allowing causality) found a positive effect of PE on IC (Browne et al., 2016; Ludyga et al., 2019; Shigeta et al., 2021). Only one study published in the last decade failed to replicate this effect (Williams et al., 2020), and a few cases reported no effects (Lind et al., 2019). When the studies compare sports intervention with no-sport conditions, a positive effect on IC could be seen in basketball, football, and badminton (Cooper et al., 2018; Lind et al., 2019; Takahashi and Grove, 2019, 2020; Wen et al., 2021). Interaction sports are characterized by abundant dynamic and constantly changing stimuli, which demand continuous regulation and adaptation. The results of a recent meta-analysis support the cognitive stimulation hypothesis, which has been proposed to explain the different temporal effects observed on cognitive performance after a single session of various activities or sports. Albaladejo-Garcia et al. (2023) found sufficient evidence to support the notion that participation in activities that demand greater cognitive effort leads to more significant adaptations in response inhibition ability. Athletes undergo physical and mental exertion during practice that requires them to monitor several cognitive processes, including focusing attention on specific cues, ignoring distractions in their environment (Laaksonen et al., 2018), and managing relevant versus irrelevant cognitive functions (Jamro et al., 2022). This effect of PE may be mediated by different factors, such as the type of activity, both quantitative (volume, intensity, density) and qualitative (continuity of exercise, conditional quality involved, and requirements) (Gutiérrez-Capote et al., 2024).

However, some issues still need to be clarified. In contrast to the cognitive benefits of a single aerobic/sports exercise session, some studies find mental fatigue-induced impairment (Dong et al., 2022). Maintaining prolonged physical exertion hurts IC (Ferreira et al., 2024), reducing activation in the dorsolateral prefrontal cortex (Ishii et al., 2014). On the other hand, exposure to the high demands of cognitive challenge experienced by the athlete during competition may decrease his or her decision-making performance, and in which IC appears to mediate (Smith et al., 2016). Cognitive-motor interference can explain this impairment (McIsaac et al., 2018). The simultaneous performance of cognitive and motor demands to which the athlete is subjected generates competition for available neural resources, leading to decreased performance in both modalities. However, studies on the chronic effect of dual-task practice have shown increased motor and cognitive performance. A recent systematic review found an acute adverse effect of dual tasks on the cognitive performance of athletes and, in turn, a benefit after training (chronic effect) with dual tasks (Moreira et al., 2021). The lack of control and monitoring of the acute effect generated by the mental load of each session of the intervention programs to investigate its relationship with the cumulative effect over time has prevented knowing what level of stimulation is required in each session to produce the desired long-term effects. From the field of sports training, it is well known that adaptations are produced through a process of supercompensation, in which it is necessary to apply a stimulus that depletes the athlete's resources so that the adaptive mechanisms are activated, which would generate an increase in their response capacity in such environments. An acute adverse effect on cognitive performance could activate the adaptive mechanisms to increase the athlete's resources of this type if temporary exposure to such environments is maintained.

Therefore, we hypothesize that the mental load of the task, generated by its level of complexity, determines the positive or negative effect on subsequent cognitive performance. Previous research conducted by Gutiérrez-Capote et al. (2023) found that by introducing difficulties through practice variability and using restrictions (motor, temporal, and spatial), players experienced an increased mental load and decreased motor performance. This type of practice succeeded in keeping participants at an optimal level of challenge (Guadagnoli and Lee, 2004). Furthermore, the effects found were moderated by previous basketball experience and the inhibition ability of the starting player, both their capacity for interference and response inhibition. Based on this background, we propose as the second hypothesis of our study that the initial experience level of the subjects modulates the magnitude of the effects.

2 Materials and methods

2.1 Ethical approval

Written informed consent was obtained from all participants prior to initiating the research. This study was approved by the Ethics Committee of the University of Granada (approval number: 3616/CEIH/2023) and conducted following the guidelines established in the Declaration of Helsinki.

2.2 Participants

The sample size was determined from an *a priori* potential analysis (G*Power version 3.1.9.7; Faul et al., 2009) for a two-way repeated ANOVA. Analysis parameters were selected from the literature review on exercise and cognition (Verburgh et al., 2014; Ludyga et al., 2016; Booth et al., 2020). An effect size of 0.25, a power (1-β) of 0.95, an expected ICC of 0.50, and an α-level of 0.05 were set for 4 group levels with a total of 9 measures, which assumed a sample size of at least 32 participants to detect similar significant effects. Before recruiting participants, the following inclusion criteria were established: (1) be free of any documented cardiovascular, neurological, psychiatric, or mental disorders; (2) be actively engaged in physical exercise or sports activities; (3) use no medication during the study period; (4) no history of concussions in the last 30 days; and (5) be free of documented muscle and musculoskeletal injuries in the previous 3 months. Forty-four students from the Faculty of Sports Sciences, who met all the previously established inclusion criteria, were selected by email after expressing their interest in participating in the study. In order to avoid the possibility that the relationship between the study variables could be influenced by chance or the results could be moderated, participants were asked to refrain from drinking alcohol 24 h before each session, to avoid caffeine for 12 h before, not to do strenuous exercise 48 h before, to sleep at least 7 h the night before and to eat a regular meal 3 h before each session.

The specialized literature (Vaughan and Edwards, 2020; Hagyard et al., 2021) emphasizes the importance of considering practical sports experience and its relationship with IC. This relationship suggests that those with more sports experience may be better able to control their actions and maintain focus during sports activity. Therefore, to mitigate the variability associated with participants' previous experiences, participants were organized into four groups based on their basketball practice in this study. Participants were differentiated according to their participation in federated competitions, their involvement in non-federated or recreational contexts, and the absence of basketball experience. The following groups were defined: High Practical Experience (HPE) for those with more than 10 years of experience in federated competitions; Medium Practical Experience (MPE) for those with 5 to 9 years of experience in federated competitions; Low Practical Experience (LPE) for individuals with practice in non-federated or recreational contexts, noting informal experience; and No Practical Experience (NPE) for those with no prior basketball experience, including both federated and non-federated contexts. Table 1 provides the profile and background information of the study participants.

2.3 Design and procedure

2.3.1 The rationale for the current design

The methodology used in the present study has been previously employed and documented (Gutiérrez-Capote et al., 2023). In that study, it was reported that players experienced an increase in perceived mental load and a decrease in motor performance under conditions involving practice variability and imposed restrictions. This previous study lays the methodological foundation for the current research, adopting a rigorous pre-experimental methodology to assess participants' baseline cognitive characteristics and previous levels in basketball. This approach is aligned with recent contributions by Anzeneder et al. (2023) and Gutiérrez-Capote et al. (2024), who stress the importance of adapting the difficulty of sports interventions to the individual characteristics of each participant in order to avoid biases derived from the lack of consideration of their starting level. Thus, the challenges presented during the experimental phase must be adjusted to the participants' previous experience. Building upon the foundation laid by the prior study, the experimental conditions were affirmed as suitable for addressing the objectives of this paper. The employed within-subject crossover design, integrating four factors, aimed to investigate the short-term impact of task restrictions during a basketball session on participants' IC ability relative to their experience level. The following is a detailed summary of the methodology and its most relevant aspects.

2.3.2 Study phases

2.3.2.1 Informative and familiarization phase

This phase was carried out in a single session, lasting approximately one and a half hours, and its main objective was to provide the participants with a complete understanding of the study. At the beginning of this session, participants were given detailed information on the research objectives, the procedures to be followed, and the instruments to be used. Next, informed consent forms signed by the participants were handed out and obtained. Subsequently, critical data for the study were recorded, including information on the years of basketball experience of each player, which was essential for their grouping by level of experience. In addition, anthropometric data were collected, such as height and weight, measurements that would facilitate the subsequent calculation of body mass index (BMI; expressed in kg/m^2). These measurements were taken with a measuring rod and a SECA 799 digital scale, with an accuracy of 0.1 kg (SECA, Germany).

2.3.2.2 Pre-experimental phase

This phase consisted of two sessions conducted on different days, for which the participants were already grouped according to their levels of basketball experience. In one of the sessions, the IC capacity

TABLE 1 Profile and background information of the study participants.

Experience group	N Male/Female	Years of practical experience	Age (years)	Height (m)	Body mass (kg)	BMI (kg·m^{-2})
HPE	*N* = 10 7/3	11.20 ± 1.23	21.10 ± 3.99	1.77 ± 0.08	74.25 ± 7.81	23.68 ± 1.85
MPE	*N* = 10 7/3	7.00 ± 1.16	19.20 ± 1.69	1.80 ± 0.07	73.52 ± 9.08	22.58 ± 1.58
LPE	*N* = 14 11/3	2.29 ± 1.07	20.64 ± 2.74	1.77 ± 0.06	68.96 ± 9.86	21.95 ± 2.31
NPE	*N* = 10 6/4	–	20.40 ± 3.89	1.70 ± 0.08	66.15 ± 7.04	22.80 ± 1.42
General	*N* = 44 31/13	–	20.36 ± 3.13	1.76 ± 0.08	70.56 ± 8.96	22.68 ± 1.90

Data values are expressed as mean ± standard deviation. HPE, High Practical Experience; MPE, Medium Practical Experience; LPE, Low Practical Experience; NPE, No Practical Experience; N, Sample Size; M, Meters; Kg, Kilograms; BMI, Body mass index.

of the participants was assessed explicitly by applying the Flanker and Go-Nogo computer-based cognitive tests (detailed in Section 2.4.1, Cognitive test, of this manuscript). This session lasted approximately 30 min. In the other session, participants' throwing ability, skill, and agility were assessed using basketball-specific tests, and their skill level was subsequently measured in a round-robin competition within each group. This session lasted approximately 1 h. A two-step cluster analysis was conducted to balance the level of competition between groups using the data collected from both sessions. This analysis allowed for pairing participants with similar abilities within each experience group, thus facilitating fair and equal competitions during the experimental sessions where participants would perform one-on-one (1 × 1) half-court basketball testing tasks. For more details on this phase, please refer to the work of Gutiérrez-Capote et al. (2023), specifically for the basketball tests used (*Physical Fitness and Sporting Ability* section, p. 8) and for the clustering analysis performed (*Clustering analysis section*, p. 5).

2.3.2.3 Experimental phase

A conventional half-court 1 × 1 basketball task was used to perform the experimental sessions. In this, the attacking player started his attack phase one step behind the 6.75-meter line, directly in front of the basket, with his defender positioned in front of him. In the case of an offense-defense change of possession, the players would start from these same spaces. This task aims to maximize the number of baskets scored on offense and minimize those received on defense. Based on this task, two experimental sessions were carried out: one maintaining standard rules marked by the basketball regulations (Regular Practice, REG) and the other in which specific restrictions were applied to increase the difficulty (Restricted Practice, RES). In the RES modality, three types of restrictions were imposed to vary the usual game conditions: (A) Motor, restricting players to a maximum of three bounces to be able to move toward the basket in each offensive possession; (B) Temporal, restricting offensive possessions to 5 s to conclude their attack, in case of not finishing their attack action in that time they lost possession of the ball in favor of the defense; and (C) Spatial, restricting offensive displacements in a central area of the half court of 14 × 4.9 meters. The following measures were taken to ensure control of the experimental conditions: (1) Sessions were scheduled at the same time of day for each pair of participants, thus mitigating the effect of diurnal variations (Thun et al., 2015); (2) A required rest of at least 72 h between sessions was established for adequate recovery; (3) The same model of ball was used during the experimental sessions, with differentiated sizes for boys (size 7) and girls (size 6). In cases of mixed pairs, there was a researcher in charge of alternating the ball between attack phases to maintain equity; and (4) The intensity of the physical load was closely monitored and controlled by applying the training load methodology of Edwards (1993) (detailed in Section 2.4.2, Training load control, of this manuscript).

The experimental sessions began with the fitting of heart rate monitors for the participants. Next, the type of session they would conduct that day was disclosed, and any questions were clarified. Next, a researcher would lead a standardized 15-min warm-up (Scanlan et al., 2018). The sessions were structured into three practice blocks, each lasting 15 min. Each block included two 7-min 1 × 1 half-court basketball tasks, with a one-minute break between tasks. For the REG, the tasks remained unchanged throughout the three blocks.

In contrast, in RES, each block was dedicated exclusively to a specific restriction, varying the type of restriction applied in each block. The sequence of restrictions applied in each block in the RES was counterbalanced among all pairs. IC assessments were conducted using the computer-based Flanker and Go-Nogo cognitive tests at the end of each block, followed by a 3-min rest period between blocks. After the IC assessment of the third block, participants had a 15-min break before proceeding to another IC assessment. The sessions concluded with a 10-min cool-down and stretch. The duration of the experimental sessions was approximately 2 h.

2.4 Variables and instruments

2.4.1 Cognitive test

Cognitive tests were conducted using the Psychological Experiment Building Language (PEBL, Version 2.1; Mueller and Piper, 2014). In the pre-experimental phase, participants were taken to a room designed to ensure a conducive environment, where computers were arranged so that participants could work comfortably and without distractions. Participants were instructed to sit comfortably, about 60 cm away from a 22″ computer screen with a black background, running the Windows operating system. These computers were equipped with a mouse, placed next to the side of the participant's dominant hand. In the case of the experimental sessions, additional measures were implemented to avoid mutual peer influence.

Consequently, the computers were set up in isolated spaces within the hall, and two researchers closely supervised each participant, ensuring the test ran smoothly. In both phases, the order of the computer tests was counterbalanced between pairs and all study participants. The tests used were:

Go-Nogo task: The task assesses response inhibition (Bezdjian et al., 2009). Participants were presented with a screen divided into four quadrants to provide a rapid and accurate motor response through a right-click when presented with a target letter. Subsequently, a single letter ("P" or "R") was displayed in one of the quadrants for a duration of 500 ms, with a 1,500 ms interval between stimuli. The experiment consisted of two distinct phases. In the initial phase, participants were instructed to respond when the letter "P" was displayed and to withhold their response when "R" appeared. In the subsequent phase, the instructions were reversed, requiring participants to respond to the letter "R" and withhold their response when "P" was presented. Each phase comprised 10 practice trials and 50 experimental trials, with a distribution of 40 trials involving target letters (e.g., P-Go) and 10 trials involving non-target letters (e.g., R-Nogo). A target-to-non-target ratio of 80:20 was maintained. The behavioral performance of the task was analyzed by: (1) the number of correct responses to the target letter (Go) (hits); (2) omission errors, which are when responding to the letter Go is missed; (3) commission errors, which refer to responding incorrectly to the letter Nogo; and (4) correct refusals to the letter Nogo. In addition, reaction time (RT), RT variability in responses to the letter Go, and the cost associated with switching between the two parts of the test were also assessed and calculated for each participant. The task duration was approximately 6 min.

Flanker task: The task assesses interference control (Eriksen and Schultz, 1979; Stins et al., 2007). In this task, participants were required to respond to the direction of a white arrow positioned in the center of the computer screen. To execute this task, participants had to press the left shift button with their left index finger when the arrow pointed to the left (“<”) and the right shift button with their right index finger when the arrow pointed to the right (“>”). The task involved four distinct flanking conditions: (1) Congruent: In this condition, all arrows pointed in the same direction (“< < <”or “> > >”); (2) Incongruent: This condition involved arrows pointing in different directions (“< < ><<” or “>>< > >”); (3) Neutral: Under this condition the central arrow is displayed alone (“<” or “>”); and (4) Dash: In this case, the central arrow lacks any distracting stimulus (“--<—-” or “-->—-”). Each testing session consisted of a block of 90 trials, including an initial set of 10 practice trials. These were followed by 20 congruent trials, 20 incongruent trials, 20 neutral trials, and 20 dash trials, presented randomly within each block. Each experimental trial commenced with a 500 ms presentation of a white fixation cross in the computer screen's background. Subsequently, a stimulus was displayed for 800 ms, with a 1,000 ms interval between stimuli. The primary variables analyzed included accuracy and average RT for each trial type. The duration of the task was approximately 6 min.

2.4.2 Training load control

It was sought to ensure that participants performed the 1 × 1 tasks within a high-intensity range commensurate with the demands of real basketball play. To this end, we relied on the results presented by Stojanović et al. (2018). In that systematic review, it was reported that maximum heart rate (HRmax) values in men and women during active participation in games fluctuated, spanning a range between 81.8 and 94.6%. By these findings, it was established that participants should perform in a range of 80–90% of their HRmax. Furthermore, this working range was considered appropriate to address the study's objectives, as cognitive performance may be affected by physical and emotional fatigue associated with high-intensity exercise (Barnes and Van Dyne, 2009). To achieve this objective, we employed Edwards' training load (Edwards, 1993) method, widely recognized in the basketball context, which allows us to evaluate both the internal training load (Manzi et al., 2010; Conte et al., 2016; Sansone et al., 2019; Camacho et al., 2021) and correlate it with the external one (Scanlan et al., 2014). This approach classifies exercise intensity into five heart rate (HR) zones about the percentage of HRmax (50–60% HRmax = 1, 60–70% HRmax = 2, 70–80% HRmax = 3, 80–90% HRmax = 4, 90–100% HRmax = 5). We calculated the percentage of each participant's HRmax using the formula 220 minus age (Fox and Naughton, 1972). Subsequently, we evaluated the training load for each participant, which allowed us, during the experimental sessions, to monitor in real-time the participants' HR using a Polar Pulsar RS800CX sensor (Polar Electro Oy, Kempele, Finland) and ensure that they were working within the optimal zone.

2.5 Statistical analysis

The data summaries, which include the mean and standard deviation, were computed for the entire sample set. Subsequently, linear mixed model analysis (LMMs) was employed, which is more appropriate in studies with repeated measures design because it considers specific patterns at the individual level, including them as random factors when correlations between the conditions of an experiment are likely to exist (Meteyard and Davies, 2020). This analysis was performed to investigate: (1) verify that the training load objective was met in both experimental conditions; (2) the impact of each experimental condition on cognitive performance (IC); (3) disparities between experimental conditions in IC; and (4) in cases where significant differences were observed, we examined whether they were mediated by basketball experience by incorporating experience groups into the session model (i.e., the model that encompassed the distinctions between the two sessions). We then evaluated the contribution of experience to model fit by comparing these models against the session model. This hierarchical analysis allowed us to determine if the increase in the proportion of explained variability attributed to the independent variable of interest (either experience or cognition) relative to a model without that independent variable justified the added complexity of the model, indicating the presence of a moderating effect.

LMMs are an extension of linear models that incorporate random effects into the linear predictor term within the regression framework. They enable the modeling of dependence structures among dependent variables, particularly in longitudinal or repeated-measures data. Model selection was based on the Akaike information criterion (AIC) and the χ^2 test to determine whether the new models provided a better fit than the session model, implying an interaction between the included variables. Furthermore, we assessed effect sizes using R^2 by Cohen's guidelines (Cohen, 1988): Weak (0.02), moderate (0.13), substantial (0.26). The model with the lower AIC was considered a better fit, signifying the existence of an interaction between the variables. The construction of each model can be observed in the first paragraph of each results section. Statistical significance was set at $p < 0.05$.

LMMs analyses used the 'lmer' function from the 'nlme' package in R (Pinheiro et al., 2012). Prior to analysis, all quantitative predictors were standardized and centered at zero. Effect sizes were calculated using the Nakagawa–Schielzeth approach (Nakagawa and Schielzeth, 2013).

3 Results

3.1 Descriptive statistics and training load check

A descriptive study of the performance variables of IC was conducted, revealing in Table 2 the means and standard deviations for each variable. As for the training load, as expected, no significant differences were observed between the blocks because it was ensured that all participants scored a 4 on Edward's scale.

3.2 LMMs–experimental condition effect on inhibitory control

The primary outcome measure was IC, assessed through Flanker and Go-Nogo tasks at baseline, across three blocks, and during the recovery phase. Each participant was treated as a random factor in

TABLE 2 Descriptives of inhibitory control performance between sessions.

	Flanker incongruent RT (ms)	Flanker congruent RT (ms)	Flanker incongruent ACC (%)	Flanker congruent ACC (%)	Go-Nogo RT (ms.)	Go-Nogo total ACC (%)	Nogo trials ACC (%) ACC (%)
Baseline	455(±42.1)	417(±45.7)	0.93(±0.05)	0.98(±0.03)	458(±55.1)	0.92(±0.03)	0.70(±0.12)
Regular practice							
Block 1	415(±38.2)**	385(±36.2)**	0.90(±0.09)*	0.97(±0.06)	396(±33.9)**	0.91(±0.04)	0.67(±0.15)*
Block 2	411(±44.0)**	377(±38.8)**	0.88(±0.10)**	0.96(±0.05)	389(±39.1)**	0.90(±0.04)	0.66(±0.16)**
Block 3	404(±42.4)**	367(±35.1)**	0.89(±0.11)**	0.97(±0.04)**	385(±29.8)**	0.91(±0.04)	0.67(±0.15)**
Recovery	415(±48.8)	379(±36.4)	0.90(±0.09)**	0.96(±0.04)	388(±32.2)**	0.90(±0.04)	0.66(±0.14)*
Restricted practice							
Block 1	470(±41.3)**	426(±38.9)**	0.85(±0.12)*	0.96(±0.04)	472(±47.3)**	0.90(±0.04)	0.59(±0.19)*
Block 2	466(±42.7)**	426(±61.3)**	0.79(±0.15)**	0.97(±0.05)	474(±46.1)**	0.90(±0.04)	0.55(±0.21)**
Block 3	465(±48.6)**	431(±68.0)**	0.76(±0.15)**	0.93(±0.06)**	477(±53.1)**	0.90(±0.04)	0.55(±0.19)**
Recovery	416(±49.3)	379(±33.8)	0.83(±0.13)**	0.96(±0.04)	434(±53.5)**	0.90(±0.04)	0.58(±0.18)*

Means and standard deviations are presented. RT, response time; ACC, accuracy; ms, milliseconds; significant differences between experimental conditions were marked with: *$p < 0.05$; **$p < 0.001$.

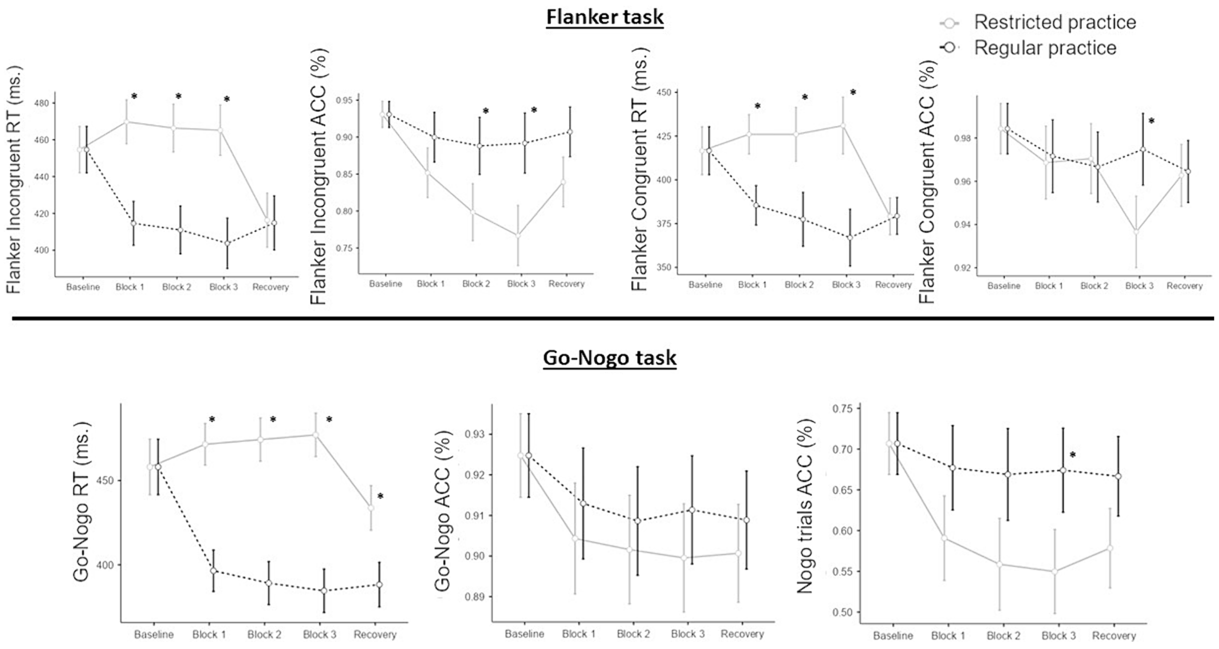


FIGURE 1
Effect of both experimental conditions in Flanker and Go-Nogo tasks. RT, response time; ACC, Accuracy. Significant differences between type of practice in each block are marked with "*".

each experimental condition (e.g., 1|participant). To ascertain whether there were changes in IC during the session, we compared baseline to the first block, analyzed differences among blocks, and evaluated differences between the last block and the recovery phase.

During the REG session, a significant reduction in RT was observed in the Flanker task for both Congruent and Incongruent trials between baseline and block 1 (Incongruent: $p < 0.001$; Congruent: $p = 0.025$). No significant differences in RT were found between subsequent blocks or the recovery phase. Additionally, no significant differences in accuracy were observed at any phase. Similar results were obtained in the Go-Nogo task.

In the RES session, no significant results were observed in RT. However, a significant decrease in accuracy was noted between baseline and block 1 in both the Flanker and Go-Nogo tasks ($p = 0.002$). These results are graphically illustrated in Figure 1.

3.3 LMMs – differences among sessions

Each participant's IC performance was the principal outcome variable of interest. Each participant was treated as a random factor, and the models involved the inclusion or exclusion of the session variable as a fixed factor. The following section presents the results, which are also visually depicted in Figure 1.

In both Congruent and Incongruent trials during the Flanker task, participants exhibited a significant deceleration in RT across all blocks within the RES session, compared to the REG session. With respect to accuracy, a notable decrease was observed in Incongruent trials during the first two blocks of the RES session. Block 3 also revealed a reduction in accuracy for Congruent trials. The sole discrepancy noted during the recovery phase was the lowered accuracy in Incongruent trials within the RES session.

In the Go-Nogo task, RT consistently demonstrated lower values in RES than those in REG across all blocks, including the recovery phase. As for accuracy, participants in the RES session committed more omission errors (pressing in Nogo trials), and this pattern was observed across all blocks, including the recovery phase.

Comprehensive details of the model results are presented in Table 3 and visually in Figure 1.

3.4 LMMs – checking the moderation by experience

New models were constructed to assess whether participants' experience levels influenced the disparities across sessions, incorporating the four experience groups and their respective IC performance. No statistically significant differences were detected at baseline. In the Incongruent trials of the Flanker task, it was observed that greater experience led to faster performance in block 1 ($p = 0.056$) and enhanced accuracy across all blocks, particularly in block 3 and the recovery block.

TABLE 3 Linear mixed models results checking differences between sessions.

Task	Block	Measure	Condition	Model	AIC	*p*-value	R^2
Flanker	1	RT	Incongruent	Without session	254.72	–	–
				Including session	219.45	<0.001	0.33
			Congruent	Including session	233.69	<0.001	0.23
	2		Incongruent	Including session	226.02	<0.001	0.29
			Congruent	Including session	238.59	<0.001	0.18
	3		Incongruent	Including session	222.01	<0.001	0.31
			Congruent	Including session	229.79	<0.001	0.26
	1	Accuracy	Incongruent	Without session	250.94	–	–
				Including session	246.99	0.014	0.04
	2		Incongruent	Without session	254.68	–	–
				Including session	245.30	<0.001	0.11
	3		Incongruent	Without session	253.77	–	–
				Including session	232.04	<0.001	0.18
			Congruent	Without session	253.53	–	–
				Including session	242.28	<0.001	0.11
	Recovery		Incongruent	Without session	254.72	–	–
				Including session	248.52	0.004	0.08
Go-Nogo	1	RT	–	Without session	254.72	–	–
			–	Including session	202.49	<0.001	0.33
	2		–	Including session	195.06	<0.001	0.34
	3		–	Including session	188.09	<0.001	0.37
	Recovery		–	Including session	235.14	<0.001	0.12
	1	Accuracy	–	Without session	247.72	–	–
			–	Including session	240.19	0.002	0.33
	2		–	Without session	254.71	–	–
			–	Including session	248.83	0.005	0.07
	3		–	Without session	252.57	–	–
			–	Including session	238.79	<0.001	0.39
	Recovery		–	Without session	253.51	–	–
			–	Including session	247.45	0.004	0.17

RT, Response time; AIC, Akaike information criterion.

TABLE 4 Linear mixed models results checking moderation by experience.

Task	Block	Model	AIC	*p*-value	R^2
Flanker (Incongruent Trials)	Block 1	Model without experience	129.85	–	–
		Model including experience	127.50	0.034	0.21
	Block 2	Model including experience	128.65	0.056	0.19
	Block 3	Model including experience	113.25	<0.001	0.43
	Recovery Block	Model without experience	−49.41	–	–
		Model including experience	−56.19	0.005	0.49
Go-Nogo	Block 1	Model without experience	129.85	–	–
	Block 1	Model including experience	122.19	0.003	0.30
	Block 3	Model including experience	121.66	0.002	0.31
	Recovery Block	Model including experience	119.83	0.001	0.34

RT, Response time; AIC, Akaike information criterion.

In the Go-Nogo task, more experience was associated with fewer omission errors during blocks 1, 3, and the recovery phase. Detailed model results are presented in Table 4 and visually depicted in Figure 2.

4 Discussion

This study aimed to examine the acute effects of sports practice on the inhibitory control of healthy young individuals. The findings revealed that altering task complexity by imposing restrictions (motor, temporal, and spatial restrictions) had an acute impact on participants' inhibitory capability. Engaging in specific and routine basketball training exercises immediately enhanced the capacity for inhibition. Conversely, engaging in more challenging tasks led to a decline in this capacity. Our study revealed that players' inhibitory control was influenced by the difficulty level of the training tasks, resulting in contrasting effects depending on the dose. These outcomes support our first hypothesis, suggesting that the level of complexity in the tasks undertaken by players determines whether there will be a positive or negative impact on their response inhibition and interference control.

When participants performed Regular Practice (REG), the result replicates the beneficial effect observed in ecological contexts in inhibitory control following a single sports bout (complex skills) compared to simple exercise without cognitive requirements (Takahashi and Grove, 2019, 2020).

According to our results, the complexity of a task influences cognitive load. Specifically, cognitively challenging exercise requiring bodily coordination demands additional cognitive effort. The more complex the task, the more significant cognitive effort is required from the individual (Paas et al., 2003). Our findings of reduced reaction time in both cognitive tasks after REG compared to the baseline state suggest that executive control was engaged during REG and that the ability to activate this control extended into the post-game period. However, the effect only persisted during the initial block. Beyond this period, reaction time levels returned to their baseline state. The acute effects of sports, involving complex motor tasks and high cognitive demands, may benefit from stimuli that pre-activate brain regions that control higher-order cognitive processes, potentially enhancing executive function (Tomporowski et al., 2015). Consequently, as evidenced by inhibitory control results, participants could process contextual information more efficiently and rapidly (Paschen et al., 2019).

On the other hand, adverse effects were also observed in the experimental condition of Restricted Practice (RES). Engagement in more challenging tasks with higher cognitive load, achieved through the imposition of restrictions (i.e., motor, temporal, and spatial), led to a decrease in inhibitory control. Specifically, unlike the REG condition, our findings regarding response accuracy in the Go-Nogo and Flanker tasks after practice, showed a significant player's accuracy reduction compared with baseline performance. This deterioration is frequently observed in studies that have tailored specific tasks to accommodate the demands of various sports, thereby investigating the repercussions of mental fatigue on cognitive abilities (Filipas et al., 2021; Fortes et al., 2023). For instance, Slimani et al. (2018) demonstrated that mental fatigue had a detrimental effect on selective attention in concentration tasks. Mental fatigue reduces the ability to suppress irrelevant information, leading participants to increasingly base their decision-making on irrelevant information, resulting in lower response accuracy (Faber et al., 2012).

As a task becomes more complex, it may demand greater attentional resources from the individual, leading to increased mental effort (Dudley et al., 2021). However, there is a limit beyond which the increase in cognitive load can overwhelm the information processing system's capacity, negatively affecting motor performance and the ability to handle additional tasks or respond to unforeseen situations (Guadagnoli and Lee, 2004). Therefore, attempting to execute the task effectively results in an immediate decrease in cognitive performance (Salihu et al., 2022).

These effects can be elucidated by the relationship between the practice of physical-cognitive exercise and enhanced top-down processing in the prefrontal cortex (Lucia et al., 2023). Physical-cognitive tasks drive inhibition by bolstering the modulation of neural processes involved in conflict monitoring (Patelaki et al., 2023). This processing is associated with a proactive type of cognitive control, whereas bottom-up processing is linked to a reactive type of control (Braver, 2012). Attention control studies suggest that difficulties in proactive control may exist in different environments and populations (Li et al., 2017). In conditions of high cognitive load, deactivation has been observed in cortical areas associated with the cognitive control network that supports top-down behavior control (Mansouri et al., 2009). On the contrary, when examining acute effects during physical tasks with cognitive demands,

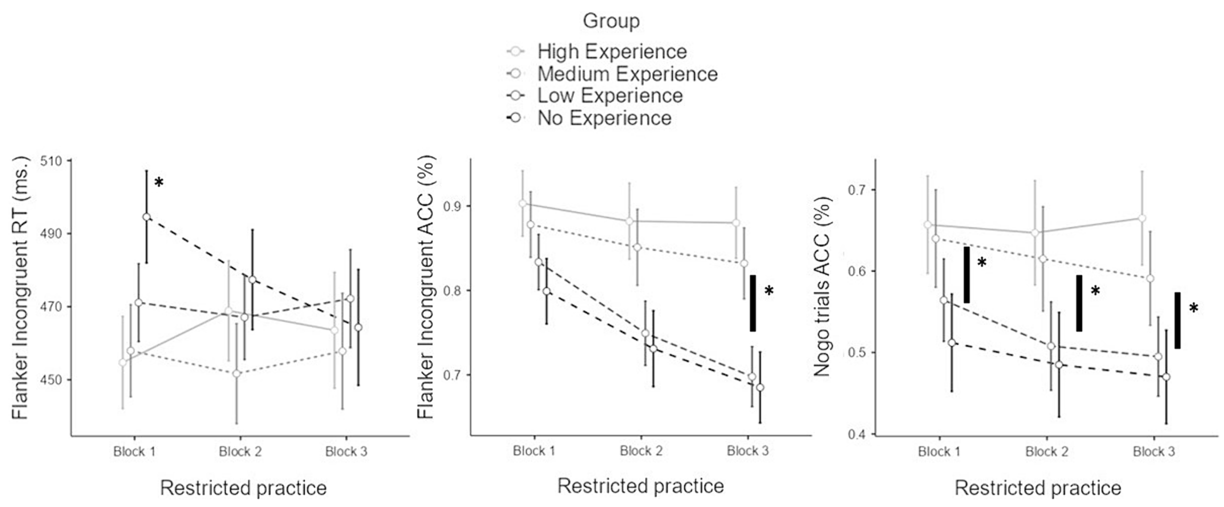


FIGURE 2
Moderation by experience in the response time and accuracy of the incongruent trials of the Flanker task and accuracy in the Nogo trials of the practice with restrictions session. RT, response time; ACC, Accuracy. Significant differences between groups of experience in each block are marked with "*".

participants who achieve benefits in their inhibitory capacity demonstrate a more proactive cognitive strategy (Patelaki et al., 2023).

The overall task context, including its demands and characteristics, is crucial in modulating proactive or reactive control strategies (Skau et al., 2021). For instance, the readiness potential (also called the Bereitschaftspotential or the premotor potential), a component of event-related potentials (ERP) extensively investigated in proactive control, is influenced by the complexity of the motor task (Colebatch, 2007). Increasing task difficulty due to increased temporal or spatial constraints may hinder proactive motor control by diminishing the player's capacity for interference anticipation (Braver et al., 2007). The Flanker and Go-Nogo tasks necessitate proactive control that could assist participants in foreseeing conflict following Incongruent or Nogo trials and preparing to halt motor responses (Liebrand et al., 2018). The extra mental effort exerted during RES could imply a shift in the type of cognitive control. In this context, it is crucial to recognize that fatigued individuals tend to employ reactive cognitive control (Brick et al., 2016; Skau et al., 2021). Therefore, our speculation is substantiated by this observation, emphasizing that subjects, when fatigued, tend to opt for reactive control over proactive control.

To conclude, the player's response would be influenced by two specific thresholds: one promoting proactive control and another impeding it. Surpassing the first threshold would enhance cognitive performance, as benefits would be activated by stimulating physical and cognitive activity with a moderate or vigorous load. However, sustaining this load over time could lead to volume-induced fatigue or increased difficulty, representing the second threshold. Surpassing this second threshold would induce an acute deterioration in cognitive performance. Thus, it is crucial to distinguish between the threshold that fosters benefits and the threshold that leads to deterioration, providing a clearer understanding of the relationship between the two. As outlined, these thresholds could be susceptible to environmental changes, such as tasks involving both physical and cognitive demands. Initially, both physical and cognitive load during RES may facilitate a shift from a more reactive to a more proactive control (Kamijo and Masaki, 2016), reverting to a reactive state again due to increased environmental demands surpassing proactive control's resources, as it is more costly and much more challenging to implement. This phenomenon has been observed in populations with fewer resources, such as older adults or children (Chevalier et al., 2012).

Finally, this study analyzed the possible influence of the players' sports experience on the relationship between the task's difficulty and their subsequent cognitive performance. The results showed the moderating effect of playing experience in attenuating the effect of increasing task difficulty on inhibitory control. Those players with more experience perceived fewer mental demands (Gutiérrez-Capote et al., 2023), translating into better results in their cognitive performance in the RES. Within the context of the optimal challenge framework, it is established that the functional difficulty of a task, in addition to being affected by experience and practice conditions, also depends on individual processing characteristics (Guadagnoli and Lee, 2004). This idea finds support in various research on elite athletes, which indicates that highly skilled athletes exhibit more efficient inhibitory control than semi-professional and amateur-level athletes (Hagyard et al., 2021). Consequently, a close relationship between the players' cognitive and athletic performance must be considered. However, future interventional research should check the direction of such a relationship. Although our results claim to be cautious, it could be that for the most experienced players the perception of the mental load required is lower when performing tasks, and, therefore, they could need fewer cognitive resources to perform them (Yu et al., 2019). Understanding this directional relationship could help design strategies to improve athletes' cognitive performance.

The mixed results on inhibitory control offer a novel perspective to interpret the dose–response effects on cognitive performance produced by increasing nominal task difficulty. However, these results should be treated with caution. Studies showing positive effects of physical exercise (PE) on inhibitory control usually compare entirely different activities (Benzing et al., 2016) and suffer from controlling for the degree of physical and mental task load through some external measure. On the other hand, studies showing the adverse effects of PE practice are limited, and it is not easy to establish a causal relationship between the results (see Egger et al. (2018)). Moreover, in their interventions, the definition of the quantitative aspects of the tasks is very disparate, and individualized adaptation was not performed.

However, the value of the results reveals the need for such an adjustment. While these environments may initially result in less adaptive behavior with more errors in the short term, challenging and practice-friendly training environments have been found to facilitate learning in the long term (Frömer, 2016). These early-stage errors could provide an essential means of stimulating an individual's adaptive capacity (Turakhia et al., 2021). Unfortunately, the design of our study does not allow us to contrast whether the acute adverse effect of cognitively more demanding practice (RES) on cognitive performance could revert to long-term benefits if these stimuli were repeated over time. Future studies should investigate the relationship between the acute and chronic effects to draw reliable conclusions.

5 Limitations

Despite finding evidence on the positive and negative effects of complexity in a task-restricted session on inhibitory control, the present study has some limitations. First, the sample size in each experience group is small and, in addition, we decided to present the results of the male and female participants together. This limitation highlights the need for a larger number of participants and the need for additional studies that can replicate these findings. However, it is essential to note that linear mixed model analysis (LMMs) was chosen for two main reasons to control for this limitation. First, it is the most appropriate approach for studies with multiple repeated measures (Meteyard and Davies, 2020). Second, this type of analysis can mitigate the limitations of having a small sample size. Since mixed effects analysis involves comparing models based on their AIC, this bears some similarity to Bayesian principles (Bozdogan, 1987). Moreover, Bayesian methods can provide meaningful results even with small samples by integrating prior information and updating beliefs with the arrival of new data. This feature is precious in contexts where data is scarce or costly (Schmid and Stanton, 2019).

Second, we tried to homogenize the level of difficulty that players would experience by facing, within each group, participants with similar skill levels in the 1 × 1 tasks. However, in the groups of less experienced players, a more in-depth evaluation would have been necessary due to the presence of participants coming from other sports disciplines, who could have had some advantage due to the transfer of learning. Finally, the availability of studies that address PE or sports interventions and report adverse effects is minimal. This paucity of research that comprehensively details and analyzes the potential adverse effects of physical activity poses a challenge to obtaining enlightening conclusions.

6 Future lines research

Future research should study the effect of learning in this type of practice. In addition, it would be interesting to study whether the short-term benefits or deterioration of cognition due to sports practice (acute effect) are reflected in the long term (chronic effect). For this purpose, it would be advisable to develop longitudinal studies in which the training loads of each session would be monitored (Perrey, 2022). In this way, evaluating the true long-term impact of stimuli that generate a post-session cognitive benefit would be possible concerning those that momentarily deteriorate cognitive performance. This would open the possibility of analyzing the cognitive development and skills acquired through sports practice, manifesting in allocating resources to improve the athlete's adaptive capacity. Exploring how practice conditions that generate greater cognitive and emotional involvement influence their subsequent cognitive performance is also interesting.

7 Conclusion and practical applications

Our findings provide a different perspective on the interaction between the complexity of an acute exercise task and subsequent cognitive performance outcomes. By introducing restrictions that modify the complexity, participants faced additional challenges, resulting in a temporary deterioration in the player's inhibitory capacity, persisting even after a 15-min recovery period. This study highlights the importance of initial levels of sports experience as significant moderators of the observed effects, thus providing a more accurate understanding of the complex interplay between exercise-induced cognitive load and its impact on cognitive performance. These aspects are essential to enhance the development of inhibitory control and test the tasks' functionality. In this sense, these approaches will help to adapt the tasks' difficulty according to each athlete's sports experience, providing an optimal challenge that favors the cognitive and adaptive growth of the players (Guadagnoli and Lee, 2004).

In terms of practical applications, these perspectives can benefit professionals in various fields, such as sports, education, recreation, or wellness, since the practitioner's observation of performance dynamics on a training task can help identify the difficulty level to stimulate the athletes' performance conservation (practice to maintain) or the performance improvement (practice to learn).

Data availability statement

The data that supports the findings of this study and the R code used are available in Figshare at https://doi.org/10.6084/m9.figshare.25772268.v1. The data is openly accessible and can be viewed online for free.

Ethics statement

The studies involving humans were approved by Ethical Committee on Human Research of the University of Granada (3616/CEIH/2023). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

10.3389/fpsyg.2024.1376961

Author contributions

AG-C: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. IM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. FA: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. ET: Data curation, Investigation, Writing – review & editing. JJ-M: Data curation, Investigation, Writing – review & editing. DC: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was funded by grants awarded by the European Regional Development Fund (ERDF) Operational Programme Andalusia 2014–2020 (Spanish Research Agency); SEJ-746-UGR20 "Effect of the manipulation of contextual variables of physical exercise on mental load and cognitive, emotional and athletic performance." Additionally, support was provided by the Camilo Cano Cathedra of Culture for Sport and Sport for Culture of the University of Alicante. Further funding was received from the Spanish Ministry of Science, Innovation, and Universities through Grant FPU19/06224 and the Spanish Ministry of Universities through Grant FPU20/02022.

Acknowledgments

The authors thank Ángel Povedano Arévalo for his invaluable help and all the participating students for collaborating with this research.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Albaladejo-Garcia, C., Garcia-Aguilar, F., and Moreno, F. J. (2023). The role of inhibitory control in sport performance: systematic review and meta-analysis in stop-signal paradigm. *Neurosci. Biobehav. Rev.* 147:105108. doi: 10.1016/j.neubiorev.2023.105108

Anzeneder, S., Zehnder, C., Martin-Niedecken, A. L., Schmidt, M., and Benzing, V. (2023). Acute exercise and children's cognitive functioning: what is the optimal dose of cognitive challenge? *Psychol. Sport Exerc.* 66:102404. doi: 10.1016/j.psychsport.2023.102404

Barnes, C. M., and Van Dyne, L. (2009). I'm tired': differential effects of physical and emotional fatigue on workload management strategies. *Hum. Relat.* 62, 59–92. doi: 10.1177/0018726708099518

Benzing, V., Heinks, T., Eggenberger, N., and Schmidt, M. (2016). Acute cognitively engaging exergame-based physical activity enhances executive functions in adolescents. *PLoS One* 11:e0167501. doi: 10.1371/journal.pone.0167501

Bezdjian, S., Baker, L. A., Lozano, D. I., and Raine, A. (2009). Assessing inattention and impulsivity in children during the Go/NoGo task. *Br. J. Dev. Psychol.* 27, 365–383. doi: 10.1348/026151008X314919

Booth, J. N., Chesham, R. A., Brooks, N. E., Gorely, T., and Moran, C. N. (2020). A citizen science study of short physical activity breaks at school: improvements in cognition and wellbeing with self-paced activity. *BMC Med.* 18, 1–11. doi: 10.1186/s12916-020-01539-4

Bozdogan, H. (1987). Model selection and Akaike's information criterion (AIC): the general theory and its analytical extensions. *Psychometrika* 52, 345–370. doi: 10.1007/BF02294361

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends Cogn. Sci.* 16, 106–113. doi: 10.1016/j.tics.2011.12.010

Braver, T. S., Gray, J. R., and Burgess, G. C. (2007). "Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control," in *Variation in working memory*. eds. A. R. A. Conway, C. Jarrold, M. C. Kane, A. Miyake, and J. N. Towse (New York: Oxford University Press), 76–106.

Bravi, R., Gavazzi, G., Benedetti, V., Giovannelli, F., Grasso, S., Panconi, G., et al. (2022). Effect of different sport environments on proactive and reactive motor inhibition: a study on open-and closed-skilled athletes via mouse-tracking procedure. *Front. Psychol.* 13:7633. doi: 10.3389/fpsyg.2022.1042705

Brick, N. E., MacIntyre, T. E., and Campbell, M. J. (2016). Thinking and action: a cognitive perspective on self-regulation during endurance performance. *Front. Physiol.* 7:159. doi: 10.3389/fphys.2016.00159

Browne, R. A. V., Costa, E. C., Sales, M. M., Fonteles, A. I., Moraes, J. F. V. N.d., and Barros, J.d. F. (2016). Acute effect of vigorous aerobic exercise on the inhibitory control in adolescents. *Rev. Paul. Pediatr.* 34, 154–161. doi: 10.1016/j.rpped.2015.08.004

Camacho, P., Cruz, D. A., Madinabeitia, I., Giménez, F. J., and Cárdenas, D. (2021). Time constraint increases mental load and influences in the performance in small-sided games in basketball. *Res. Q. Exerc. Sport* 92, 443–452. doi: 10.1080/02701367.2020.1745138

Chevalier, N., Sheffield, T. D., Nelson, J. M., Clark, C. A., Wiebe, S. A., and Espy, K. A. (2012). Underpinnings of the costs of flexibility in preschool children: the roles of inhibition and working memory. *Dev. Neuropsychol.* 37, 99–118. doi: 10.1080/87565641.2011.632458

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. New York, NY: Academic, 54.

Colebatch, J. G. (2007). Bereitschaftspotential and movement-related potentials: origin, significance, and application in disorders of human movement. *Mov. Disord.* 22, 601–610. doi: 10.1002/mds.21323

Conte, D., Favero, T. G., Niederhausen, M., Capranica, L., and Tessitore, A. (2016). Effect of different number of players and training regimes on physiological and technical demands of ball-drills in basketball. *J. Sports Sci.* 34, 780–786. doi: 10.1080/02640414.2015.1069384

Cooper, S. B., Dring, K. J., Morris, J. G., Sunderland, C., Bandelow, S., and Nevill, M. E. (2018). High intensity intermittent games-based activity and adolescents' cognition: moderating effect of physical fitness. *BMC Public Health* 18, 1–14. doi: 10.1186/s12889-018-5514-6

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Dong, L., Pageaux, B., Romeas, T., and Berryman, N. (2022). The effects of fatigue on perceptual-cognitive performance among open-skill sport athletes: a scoping review. *Int. Rev. Sport Exerc. Psychol.* 42, 1–52. doi: 10.1080/1750984X.2022.2135126

Dudley, D., Dean, H., Cairney, J., and Van Bergen, P. (2021). Pedagogical constraints of physical literacy based on cognitive load theory. *Prospects* 50, 151–164. doi: 10.1007/s11125-020-09496-9

Edwards, S. (1993). High performance training and racing. *Heart Rate Monitor Book* 349, 113–123,

Egger, F., Conzelmann, A., and Schmidt, M. (2018). The effect of acute cognitively engaging physical activity breaks on children's executive functions: too much of a good thing? *Psychol. Sport Exerc.* 36, 178–186. doi: 10.1016/j.psychsport.2018.02.014

Eriksen, C. W., and Schultz, D. W. (1979). Information processing in visual search: a continuous flow conception and experimental results. *Percept. Psychophys.* 25, 249–263. doi: 10.3758/BF03198804

Faber, L. G., Maurits, N. M., and Lorist, M. M. (2012). Mental fatigue affects visual selective attention. *PLoS One* 7:e48073. doi: 10.1371/journal.pone.0048073

Faul, F., Erdfelder, E., Buchner, A., and Lang, A.-G. (2009). Statistical power analyses using G* power 3.1: tests for correlation and regression analyses. *Behav. Res. Methods* 41, 1149–1160. doi: 10.3758/BRM.41.4.1149

Ferreira, M. E., Lima-Junior, D., Faro, H., Roelands, B., and Fortes, L. S. (2024). Prolonged cognitive effort impairs inhibitory control and causes significant mental fatigue after an endurance session with an auditive distractor in professional soccer players. *Psychol. Sport Exerc.* 70:102533. doi: 10.1016/j.psychsport.2023.102533

Filipas, L., Borghi, S., La Torre, A., and Smith, M. R. (2021). Effects of mental fatigue on soccer-specific performance in young players. *Sci. Med. Footb.* 5, 150–157. doi: 10.1080/24733938.2020.1823012

Fortes, L. S., Gantois, P., de Lima-Junior, D., Barbosa, B. T., Ferreira, M. E. C., Nakamura, F. Y., et al. (2023). Playing videogames or using social media applications on smartphones causes mental fatigue and impairs decision-making performance in amateur boxers. *Appl. Neuropsychol. Adult* 30, 227–238. doi: 10.1080/23279095.2021.1927036

Fox, S. M. III, and Naughton, J. P. (1972). Physical activity and the prevention of coronary heart disease. *Prev. Med.* 1, 92–120. doi: 10.1016/0091-7435(72)90079-5

Frömer, R. (2016). *Learning to throw: contributions of contextual interference and individual differences to the acquisition of a complex motor skill: an investigation with event-related brain potentials*. Berlin: Humboldt Universität zu Berlin, 2016.

Guadagnoli, M. A., and Lee, T. D. (2004). Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. *J. Mot. Behav.* 36, 212–224. doi: 10.3200/JMBR.36.2.212-224

Gutiérrez-Capote, A., Jiménez-Martínez, J., Madinabeitia, I., de Orbe-Moreno, M., Pesce, C., and Cardenas, D. (2024). Sport as cognition enhancer from childhood to young adulthood: a systematic review focused on sport modality. *Int. J. Sport Exerc. Psychol.* 22, 395–427. doi: 10.1080/1612197X.2023.2289552

Gutiérrez-Capote, A., Madinabeitia, I., Torre, E., Alarcón, F., Jiménez-Martínez, J., and Cárdenas, D. (2023). Changes in perceived mental load and motor performance during practice-to-learn and practice-to-maintain in basketball. *Int. J. Environ. Res. Public Health* 20:4664. doi: 10.3390/ijerph20054664

Hagyard, J., Brimmell, J., Edwards, E. J., and Vaughan, R. S. (2021). Inhibitory control across athletic expertise and its relationship with sport performance. *J. Sport Exerc. Psychol.* 43, 14–27. doi: 10.1123/jsep.2020-0043

Ishii, A., Tanaka, M., and Watanabe, Y. (2014). Neural mechanisms of mental fatigue. *Rev. Neurosci.* 25, 469–479. doi: 10.1515/revneuro-2014-0028

Jamro, D., Zurek, G., Dulnik, M., Lachowicz, M., and Lenart, D. (2022). Executive function level in cadets' shooting performance. *Int. J. Environ. Res. Public Health* 19:6007. doi: 10.3390/ijerph19106007

Kamijo, K., and Masaki, H. (2016). Fitness and ERP indices of cognitive control mode during task preparation in preadolescent children. *Front. Hum. Neurosci.* 10:441. doi: 10.3389/fnhum.2016.00441

Laaksonen, M. S., Finkenzeller, T., Holmberg, H.-C., and Sattlecker, G. (2018). The influence of physiobiomechanical parameters, technical aspects of shooting, and psychophysiological factors on biathlon performance: a review. *J. Sport Health Sci.* 7, 394–404. doi: 10.1016/j.jshs.2018.09.003

Li, J. W., O'Connor, H., O'Dwyer, N., and Orr, R. (2017). The effect of acute and chronic exercise on cognitive function and academic performance in adolescents: a systematic review. *J. Sci. Med. Sport* 20, 841–848. doi: 10.1016/j.jsams.2016.11.025

Liao, K.-F., Meng, F.-W., and Chen, Y.-L. (2017). The relationship between action inhibition and athletic performance in elite badminton players and non-athletes. *J. Hum. Sport Exerc.* 12, 574–581. doi: 10.14198/jhse.2017.123.02

Liebrand, M., Kristek, J., Tzvi, E., and Krämer, U. M. (2018). Ready for change: oscillatory mechanisms of proactive motor control. *PLoS One* 13:e0196855. doi: 10.1371/journal.pone.0196855

Lind, R. R., Beck, M. M., Wikman, J., Malarski, K., Krustrup, P., Lundbye-Jensen, J., et al. (2019). Acute high-intensity football games can improve children's inhibitory control and neurophysiological measures of attention. *Scand. J. Med. Sci. Sports* 29, 1546–1562. doi: 10.1111/sms.13485

Lucia, S., Bianco, V., and Di Russo, F. (2023). Specific effect of a cognitive-motor dual-task training on sport performance and brain processing associated with decision-making in semi-elite basketball players. *Psychol. Sport Exerc.* 64:102302. doi: 10.1016/j.psychsport.2022.102302

Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., and Pühse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: a meta-analysis. *Psychophysiology* 53, 1611–1626. doi: 10.1111/psyp.12736

Ludyga, S., Pühse, U., Lucchi, S., Marti, J., and Gerber, M. (2019). Immediate and sustained effects of intermittent exercise on inhibitory control and task-related heart rate variability in adolescents. *J. Sci. Med. Sport* 22, 96–100. doi: 10.1016/j.jsams.2018.05.027

Mansouri, F. A., Tanaka, K., and Buckley, M. J. (2009). Conflict-induced behavioural adjustment: a clue to the executive functions of the prefrontal cortex. *Nat. Rev. Neurosci.* 10, 141–152. doi: 10.1038/nrn2538

Manzi, V., D'Ottavio, S., Impellizzeri, F. M., Chaouachi, A., Chamari, K., and Castagna, C. (2010). Profile of weekly training load in elite male professional basketball players. *J. Strength Cond. Res.* 24, 1399–1406. doi: 10.1519/JSC.0b013e3181d7552a

McIsaac, T. L., Fritz, N. E., Quinn, L., and Muratori, L. M. (2018). Cognitive-motor interference in neurodegenerative disease: a narrative review and implications for clinical management. *Front. Psychol.* 9:360222. doi: 10.3389/fpsyg.2018.02061

Meteyard, L., and Davies, R. A. (2020). Best practice guidance for linear mixed-effects models in psychological science. *J. Mem. Lang.* 112:104092. doi: 10.1016/j.jml.2020.104092

Miyake, A., Friedman, N., Emerson, M., Witzki, A., Howerter, A., and Wager, T. (2000). La unidad y diversidad de las funciones ejecutivas y sus contribuciones a tareas complejas del "lobulo frontal": un análisis de variables latentes. *Psicol. Cogn.* 41, 49–100. doi: 10.1006/cogp.1999.0734

Moreira, P. E. D., Dieguez, G. T.d. O., Bredt, S.d. G. T., and Praça, G. M. (2021). The acute and chronic effects of dual-task on the motor and cognitive performances in athletes: a systematic review. *Int. J. Environ. Res. Public Health* 18:1732. doi: 10.3390/ijerph18041732

Mueller, S. T., and Piper, B. J. (2014). The psychology experiment building language (PEBL) and PEBL test battery. *J. Neurosci. Methods* 222, 250–259. doi: 10.1016/j.jneumeth.2013.10.024

Nakagawa, S., and Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods Ecol. Evol.* 4, 133–142. doi: 10.1111/j.2041-210x.2012.00261.x

Paas, F., Tuovinen, J. E., Tabbers, H., and Van Gerven, P. W. M. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educ. Psychol.* 38, 63–71.

Paschen, L., Lehmann, T., Kehne, M., and Baumeister, J. (2019). Effects of acute physical exercise with low and high cognitive demands on executive functions in children: a systematic review. *Pediatr. Exerc. Sci.* 31, 267–281. doi: 10.1123/pes.2018-0215

Patelaki, E., Foxe, J. J., Mazurek, K. A., and Freedman, E. G. (2023). Young adults who improve performance during dual-task walking show more flexible reallocation of cognitive resources: a mobile brain-body imaging (MoBI) study. *Cereb. Cortex* 33, 2573–2592. doi: 10.1093/cercor/bhac227

Perrey, S. (2022). Training monitoring in sports: it is time to embrace cognitive demand. *Sports* 10:56. doi: 10.3390/sports10040056

Pinheiro, J., Bates, D., DebRoy, S., and Sarkar, D. (2012). Nonlinear mixed-effects models. R package version 3, 1–89.

Salihu, A. T., Hill, K. D., and Jaberzadeh, S. (2022). Effect of cognitive task complexity on dual task postural stability: a systematic review and meta-analysis. *Exp. Brain Res.* 240, 703–731. doi: 10.1007/s00221-021-06299-y

Sansone, P., Tessitore, A., Paulauskas, H., Lukonaitiene, I., Tschan, H., Pliauga, V., et al. (2019). Physical and physiological demands and hormonal responses in basketball small-sided games with different tactical tasks and training regimes. *J. Sci. Med. Sport* 22, 602–606. doi: 10.1016/j.jsams.2018.11.017

Scanlan, A. T., Wen, N., Spiteri, T., Milanović, Z., Conte, D., Guy, J. H., et al. (2018). Dribble deficit: a novel method to measure dribbling speed independent of sprinting speed in basketball players. *J. Sports Sci.* 36, 2596–2602. doi: 10.1080/02640414.2018.1470217

Scanlan, A. T., Wen, N., Tucker, P. S., and Dalbo, V. J. (2014). The relationships between internal and external training load models during basketball training. *J. Strength Cond. Res.* 28, 2397–2405. doi: 10.1519/JSC.0000000000000458

Scharfen, H. E., and Memmert, D. (2019). Measurement of cognitive functions in experts and elite athletes: a meta-analytic review. *Appl. Cogn. Psychol.* 33, 843–860. doi: 10.1002/acp.3526

Schmid, D., and Stanton, N. A. (2019). Exploring Bayesian analyses of a small-sample-size factorial design in human systems integration: the effects of pilot incapacitation. *Hum.-Intell. Syst. Integr.* 1, 71–88. doi: 10.1007/s42454-020-00012-0

Shigeta, T. T., Morris, T. P., Henry, D. H., Kucyi, A., Bex, P., Kramer, A. F., et al. (2021). Acute exercise effects on inhibitory control and the pupillary response in young adults. *Int. J. Psychophysiol.* 170, 218–228. doi: 10.1016/j.ijpsycho.2021.08.006

Skau, S., Bunketorp-Käll, L., Johansson, B., and Kuhn, H.-G. (2021). Different properties of the hemodynamic response and its relation to trait mental fatigue and proactive cognitive control. *Neuroimage* 1:100038. doi: 10.1016/j.ynirp.2021.100038

Slimani, M., Znazen, H., Bragazzi, N. L., Zguira, M. S., and Tod, D. (2018). The effect of mental fatigue on cognitive and aerobic performance in adolescent active endurance athletes: insights from a randomized counterbalanced, cross-over trial. *J. Clin. Med.* 7:510. doi: 10.3390/jcm7120510

Smith, M. R., Zeuwts, L., Lenoir, M., Hens, N., De Jong, L. M., and Coutts, A. J. (2016). Mental fatigue impairs soccer-specific decision-making skill. *J. Sports Sci.* 34, 1297–1304. doi: 10.1080/02640414.2016.1156241

Stins, J. F., Polderman, J. T., Boomsma, D. I., and de Geus, E. J. (2007). Conditional accuracy in response interference tasks: evidence from the Eriksen flanker task and the spatial conflict task. *Adv. Cogn. Psychol.* 3, 409–417. doi: 10.2478/v10053-008-0005-4

Stojanović, E., Stojiljković, N., Scanlan, A. T., Dalbo, V. J., Berkelmans, D. M., and Milanović, Z. (2018). The activity demands and physiological responses encountered during basketball match-play: a systematic review. *Sports Med.* 48, 111–135. doi: 10.1007/s40279-017-0794-z

Swann, C., Moran, A., and Piggott, D. (2015). Defining elite athletes: issues in the study of expert performance in sport psychology. *Psychol. Sport Exerc.* 16, 3–14. doi: 10.1016/j.psychsport.2014.07.004

Takahashi, S., and Grove, P. M. (2019). Comparison of the effects of running and badminton on executive function: a within-subjects design. *PLoS One* 14:e0216842. doi: 10.1371/journal.pone.0216842

Takahashi, S., and Grove, P. M. (2020). Use of stroop test for sports psychology study: cross-over design research. *Front. Psychol.* 11:614038. doi: 10.3389/fpsyg.2020.614038

Thun, E., Bjorvatn, B., Flo, E., Harris, A., and Pallesen, S. (2015). Sleep, circadian rhythms, and athletic performance. *Sleep Med. Rev.* 23, 1–9. doi: 10.1016/j.smrv.2014.11.003

Tomporowski, P. D., McCullick, B., Pendleton, D. M., and Pesce, C. (2015). Exercise and children's cognition: the role of exercise characteristics and a place for metacognition. *J. Sport Health Sci.* 4, 47–55. doi: 10.1016/j.jshs.2014.09.003

Tsai, C.-L. (2009). The effectiveness of exercise intervention on inhibitory control in children with developmental coordination disorder: using a visuospatial attention paradigm as a model. *Res. Dev. Disabil.* 30, 1268–1280. doi: 10.1016/j.ridd.2009.05.001

Turakhia, D.G., Qi, Y., Blumberg, L.-G., Wong, A., and Mueller, S. (2021). "Can physical tools that adapt their shape based on a learner's performance help in motor skill training?" in *Proceedings of the fifteenth international conference on tangible, embedded, and embodied interaction*. Salzburg, Austria, 1–12.

Vaughan, R. S., and Edwards, E. J. (2020). Executive function and personality: the moderating role of athletic expertise. *Personal. Individ. Differ.* 161:109973. doi: 10.1016/j.paid.2020.109973

Verburgh, L., Königs, M., Scherder, E. J., and Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: a meta-analysis. *Br. J. Sports Med.* 48, 973–979. doi: 10.1136/bjsports-2012-091441

Wen, X., Yang, Y., and Wang, F. (2021). Influence of acute exercise on inhibitory control and working memory of children: a comparison between soccer, resistance, and coordinative exercises. *Int. J. Sport Psychol.* 52, 101–119. doi: 10.7352/IJSP.2021.52.101

Williams, R. A., Cooper, S. B., Dring, K. J., Hatch, L., Morris, J. G., Sunderland, C., et al. (2020). Effect of football activity and physical fitness on information processing, inhibitory control and working memory in adolescents. *BMC Public Health* 20, 1–14. doi: 10.1186/s12889-020-09484-w

Xie, L., Ren, M., Cao, B., and Li, F. (2017). Distinct brain responses to different inhibitions: evidence from a modified flanker task. *Sci. Rep.* 7:6657. doi: 10.1038/s41598-017-04907-y

Yu, Q., Chau, B. K., Lam, B. Y., Wong, A. W., Peng, J., and Chan, C. C. (2019). Neural processes of proactive and reactive controls modulated by motor-skill experiences. *Front. Hum. Neurosci.* 13:404. doi: 10.3389/fnhum.2019.00404

frontiers | Frontiers in Human Neuroscience

TYPE Systematic Review
PUBLISHED 05 September 2024
DOI 10.3389/fnhum.2024.1418803

The frontal association area: exercise-induced brain plasticity in children and adolescents and implications for cognitive intervention practice

Ziyun Zhang[1], Peng Shi[2]*, Kai Zhang[2,3,4], Chenyang Li[5] and Xiaosu Feng[6]

[1]School of Life and Health, Huzhou College, Huzhou, China, [2]School of Physical Education, Shanghai University of Sport, Shanghai, China, [3]School of Physical Education, Shandong University of Aeronautics, Binzhou, China, [4]Department of Graduate Studies, Shenyang Sport University, Shenyang, China, [5]Department of Physical Education, Huaiyin Institute of Technology, Huaian, China, [6]School of Physical Education, Liaoning Normal University, Dalian, China

Check for updates

OPEN ACCESS

EDITED BY
Jose Mora-Gonzalez,
University of Granada, Spain

REVIEWED BY
Federico d'Oleire Uquillas,
Princeton University, United States
Lanxin Ji,
New York University, United States
Luca Petrigna,
University of Catania, Italy

*CORRESPONDENCE
Peng Shi
✉ 1658585524@qq.com

RECEIVED 17 April 2024
ACCEPTED 15 August 2024
PUBLISHED 05 September 2024

CITATION
Zhang Z, Shi P, Zhang K, Li C and Feng X (2024) The frontal association area: exercise-induced brain plasticity in children and adolescents and implications for cognitive intervention practice. *Front. Hum. Neurosci.* 18:1418803. doi: 10.3389/fnhum.2024.1418803

Objective: Explore the plasticity of the frontal associative areas in children and adolescents induced by exercise and potential moderating variables.

Methods: Computer searches of CNKI, WOS, PubMed and EBSCO databases were conducted, and statistical analyses were performed based on SPSS 25.0, Stata 12.0 and Ginger ALE 2.3 software after literature screening, data extraction and quality assessment were performed independently by two researchers.

Results: A total of 13 articles, including 425 participants aged 8.9~16.8 years, were included. Frequency analysis revealed that exercise induced enhanced activation in frontal, parietal, occipital, limbic system and cerebellum ($P < 0.01$). Activation Likelihood Estimation (ALE) meta-analysis revealed that exercise altered the activation status of the frontal association (medial frontal gyrus, middle frontal gyrus, inferior frontal gyrus and precentral gyrus), cuneus, lingual gyrus, cingulate gyrus, parahippocampal gyrus, caudate nucleus and cerebellar apex, with the volume of activation in the frontal association accounting for 61.81% of the total activation cluster volume and an enhanced activation effect. Additionally, the study design, age, gender, nationality, cognitive tasks, as well as exercise intensity, intervention time, and type of exercise may be potential moderating variables. Particularly, sustained exercise induced a decrease in activation in the left parahippocampal gyrus, culmen, and lingual gyrus, while variable exercise induced an increase in activation in the left middle frontal gyrus.

Conclusion: Exercise-induced activation increase in the frontal associative areas of children and adolescents is dominant, especially longer periods of moderate-intensity variable exercise can induce more brain region activation. However, some of the included studies are cross-sectional, and the accuracy of the results still requires further verification.

Systematic review registration: https://www.crd.york.ac.uk/prospero/, identifier PROSPERO, CRD42022348781.

KEYWORDS

frontal association area, brain, neuroplasticity, fMRI, exercise, ALE meta-analysis

1 Introduction

The human brain is an extremely complex functional system that controls all thoughts and actions of the individual. The frontal association area is the higher management center for the formation and control of various behaviors and is closely associated with higher cognitive functions such as executive control, working memory, logical reasoning and fluid intelligence (Carlén, 2017; Eimontaite et al., 2018; Kane and Engle, 2002; Welsh et al., 1991). Additionally, the higher-order literacies of children and adolescents, such as logical thinking, analysis, synthesis, reasoning, deduction, induction, and hypothesis (Cai, 2014), as well as their autonomous and conscious actions and complex communication (Teng, 2016), are all regulated by the frontal association area. Based on this, Pan (2018) proposed a hypothesis that the development of students' advanced literacy skills could be promoted in accordance with the developmental laws of the prefrontal cortex. Against this backdrop, how to promote the plasticity of the frontal association area in children and adolescents has become a focal point of research in various fields.

A series of studies have confirmed that exercise can induce neuroplasticity in the prefrontal association area, thereby improving cognitive performance. For example, Activation Likelihood Estimation (ALE) meta-analyses have shown that exercise induces significant activation of prefrontal brain areas such as the superior frontal gyrus (Wu et al., 2022) and inferior frontal gyrus (Cui et al., 2019) in executive control task activities. Changes in brain activation states induced by exercise are common and possess temporal and spatial characteristics (Cui et al., 2019; Li and Zhang, 2023). The temporal feature refers to the changes in brain activation states before and after exercise intervention. The spatial feature refers to the changes in the spatial location of brain activation after exercise intervention, mainly including three patterns: activation enhancement, activation reduction, and activation re-organized (Cui et al., 2019). Activation enhancement refers to the increase in the activation volume of relevant brain regions after the intervention. Activation reduction refers to the decrease in the activation volume of relevant brain regions after the intervention. Activation re-organized refers to the phenomenon where after the intervention, the activation volume of relevant brain regions coexists with both enhancement and reduction, resulting in a new layout. The spatio-temporal characteristics of exercise-induced neuroplasticity can be explained by the Extended Frontoparietal Integration Theory (Gur et al., 2021) and the Neural Efficiency Hypothesis (Chen et al., 2022). The former considers cognitive and thinking activities to be the result of the synergistic action of various brain areas, including the frontal, parietal, temporal, occipital, limbic system, striatum and cerebellum (Gur et al., 2021; Jung and Haier, 2007). The latter is more supportive of the idea that "smart brains are lazy", that is, that individuals use fewer neural resources to complete cognitive tasks (Chen et al., 2022). Based on the central role of the frontal association area in cognitive tasks and previous studies (Chen et al., 2022; Li and Zhang, 2023), this hypothesis can be derived: Exercise induces a reorganization of activation in a series of brain regions, with a more significant increase in activation in the frontal association area. However, this hypothesis still requires further verification and argumentation.

In addition, after a comprehensive review of the relevant studies in this field, several important limitations have indeed been identified. Firstly, there are significant inconsistencies or even complete contradictions in the results of different studies regarding the impact of exercise on brain plasticity in children and adolescents. For instance, Krafft et al. (2014) found that after exercise intervention, children showed increased activation in the frontal medial gyrus, frontal middle gyrus, and other frontal lobe regions during the Flanker task. However, Herting and Nagel (2013) discovered that children with high aerobic fitness generally showed decreased activation in brain regions during verbal associative memory encoding tasks. Secondly, while there have been systematic reviews (Meijer et al., 2020; Wassenaar et al., 2020; Valkenborghs et al., 2019) studying the effects of exercise on brain plasticity in children and adolescents, the conclusions drawn from these reviews need to be treated with caution as they are primarily based on qualitative analysis. Therefore, there is still a need for more rigorous quantitative methods such as ALE meta-analysis to assess changes in brain activation states. However, there is still a scarcity of relevant research on children and adolescents, limiting our in-depth understanding of the changes in brain plasticity in this specific group. Lastly, although Li and Zhang (2023) have recognized the importance of quantitatively integrating research findings, they have not yet fully taken into account potential moderating factors, thereby overlooking the heterogeneity that may exist.

Differences in study design, sample characteristics, exercise characteristics, and task paradigms may be the reasons for inconsistencies among original studies. Specifically, the characteristics of exercise type, intensity, and period can have significantly different cognitive benefits on the human brain (Heilmann et al., 2022; Liu, 2017). Regarding the type of exercise, exercises that induce more cognitive challenges are more likely to produce greater cognitive advantages compared to continuous aerobic exercise (Shi and Feng, 2022; Shi et al., 2022). Based on this, Shi et al. (2023) categorized exercise types into variable exercise and sustained exercise, and called on researchers to explore the differences in cognitive benefits and brain plasticity resulting from these two types of exercise. Variable exercise refers to exercise types with relatively complex movements and action structures, which mainly promote perceptual-motor skills, agility, and coordination (Mansouri et al., 2009; Pesce et al., 2019). Examples include open skills like basketball and football, as well as closed-sequential skills like aerobics and martial arts. Sustained exercise, on the other hand, refers to exercise types with relatively simple movement structures and actions without clear beginnings or ends, which mainly develop cardiorespiratory fitness (Zhu et al., 2014). These include activities like running, swimming, and cycling. Based on this, this study focuses on exploring the potential role of exercise types while investigating potential moderating factors, and puts forward the hypothesis that there exists heterogeneity in the brain activation induced by variable exercise and sustained exercise.

This study aims to systematically review research on brain activation induced by exercise in children and adolescents, and to explore whether the brain plasticity induced by exercise conforms to the Extended Frontoparietal Integration Theory and the Neural Efficiency Hypothesis using ALE meta-analysis. On this basis, this study further aims to investigate the moderating variables of exercise-induced brain plasticity and to explore the optimal set of elements that promote brain plasticity. Through this study, we hope to provide theoretical and practical references for research related to promoting brain health and cognitive functions in children and adolescents through exercise, and to offer guidance for neuroscientific- based physical education practices.

2 Materials and methods

This ALE meta-analysis was registered (CRD42022348781) in the International Prospective Register of Systematic Reviews (PROSPERO). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines were followed for this study.

2.1 Search strategies

A search of the relevant articles was conducted by one researcher using both English and Chinese search terms. This study employs the following search strings for literature retrieval in the CNKI, Web of Science (WOS), PubMed, and EBSCO databases. The example of a search string in the WOS database is as follows: (TS = (((exercise OR sports OR fitness OR physical activity) AND (magnetic resonance OR brain imaging OR brain function OR brain activation OR functional MRI OR fMRI) AND (children OR child OR adolescents OR young OR teenagers OR kindergarten)))) NOT TS = ((concussion OR brain injury OR injury)). In addition, recent systematic reviews and Meta-analyses were searched as well as references back to included studies to avoid omissions. The search time frame is from the creation of this database to June 2024.

2.2 Selection criteria

This study designed the inclusion and exclusion criteria for the literature according to the Population, Intervention, Comparison, Outcomes and Study (PICOS) principles (Costantino et al., 2015). Inclusion criteria: (1) subjects were typical children and adolescents; (2) interventions or exposures were acute or long-term exercise; (3) controls included routine academic life, attention and behavioral control, irregular exercise and sedentary; (4) outcome variables included functional magnetic resonance imaging (fMRI) tasks and brain activation results; (5) study designs included randomized controlled trial (RCT), quasi-experimental design (QED) and cross- sectional study (CSS). Exclusion criteria: (1) special groups such as athletes, pilots, police, military, and atypical groups with cognitive or intellectual impairment; (2) comprehensive interventions such as exercise combined with diet control, exercise combined with cognitive therapy; (3) studies in which detailed information is not available such as reviews, abstracts, letters, comments; (4) resting-state MRI studies; (5) repeated publications on the same study subjects, including only those of high quality; (6) literature with missing or incomplete data (MNI or Talairach coordinates) in the literature. Selection was carried out independently by two researchers, with the other two researchers carrying out a secondary assessment of the screened articles, and where there was controversial article, the group discussed and agreed together.

2.3 Data extraction

By thoroughly reading the included literature, the following data are extracted: (1) bibliographic information, including the first author and the year of publication; (2) study design, including RCT, QED, or CSS; (3) basic information of participants, including sample size, age, proportion of female participants, and nationality; (4) intervention or exposure measures, including exercise methods (categorized into variable exercise and sustained exercise based on exercise type), exercise intensity (low, moderate, and high), exercise duration (acute and long-term), frequency, single time, and total intervention time (calculated based on the formula "duration × frequency × single time"); (5) control measures; (6) cognitive task paradigms used during fMRI, such as inhibitory control tasks like Flanker, GO/NO GO, and working memory tasks like N-back; (7) brain coordinate positioning systems adopted in the research, including MNI and Talairach; (8) brain activation areas and their activation coordinates. In this study, the extracts were entered into Excel 2010 and saved. The data extraction is carried out independently by two researchers and the extraction is secondarily assessed by the other two researchers, and if there is a dispute, the group discusses and decides together.

2.4 Quality assessment

This quality assessment of RCTs was performed using the Cochrane Collaboration Risk of Bias Tool (Cumpston et al., 2019). The tool assesses six aspects of randomized methods, blinding, allocation concealment, completeness of outcome data, selective reporting of study results and other biases. The Methodological Index for Non-Randomized Studies (MINORS) scale (Slim et al., 2003) was used to assess the quality of QEDs. The tool consists of 12 items, with 9 to 12 additional criteria for assessing studies with a control group, each with a score of 2, for a total score of 24. A score of 0 means not reported; a score of 1 means reported but with insufficient information; a score of 2 means reported and sufficient information provided. The Agency for Healthcare Research and Quality (AHRQ) scale (Bindman, 2017) was used to assess the quality of CSSs. The tool consists of 11 items and the assessor is asked to assess each item using "yes", "no" and "unclear". Given that the CSS were all human experiments and there was no follow-up, items 4 and 9 were excluded and only 9 items were assessed for quality. Judgments based on the assessment tool were made independently by two researchers and, where there was significant disagreement, the items were discussed with a third researcher.

2.5 Data analysis

Firstly, this study was based on SPSS 25.0 and Stata 12.0 software, using frequency analysis and χ^2 tests to explore exercise-induced increased and decreased activation in brain areas. In addition, this study employs regression analysis to investigate the association between the total intervention time and the number of activated brain regions. Secondly, this study used ALE meta-analysis to examine the brain activation state reflected by exercise-induced fMRI data. Based on Ginger ALE 2.3 software for ALE

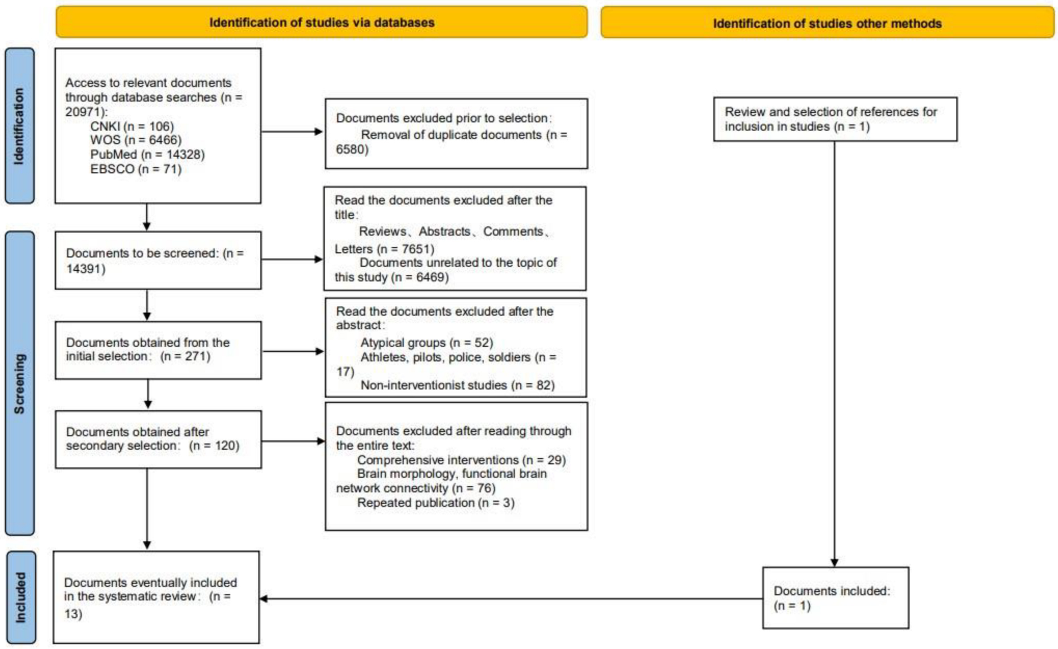


FIGURE 1
Flow chart for literature selection.

meta-analysis under the Talairach spatial standard, Lancaster was used to convert the coordinates reported in the MNI spatial standard to Talairach coordinates (Lancaster et al., 2007). Referring to the algorithm and parameter setting recommendations provided in the Ginger ALE manual, the FDR pID algorithm was chosen for this study, with a critical statistical value of 0.001 and a minimum volume setting of 200 mm (Eickhoff et al., 2009), to calculate exercise-induced brain activation clusters and their maximum ALE values (maximum ALE values indicate the probability of activation of brain areas). Thirdly, based on Mango 4.0 software and referring to previous study (Wu et al., 2022), the activation coordinates of brain regions from the ALE meta-analysis were superimposed onto a standard brain image (Colin_tlrc_2x2x2 from)[1] to visualize the results of this study.

Finally, to verify whether the ALE results overlap with the frontal association area or other brain networks, this study adopted the method of Meta-Analytic Connectivity Modeling (MACM), following the procedure implemented by Robinson et al. (2010) in NeuroSynth.[2] This study used activation clusters as the regions of interest (ROI) derived from the ALE results and input them into the NeuroSynth program to evaluate MACM. The program searched for studies reporting activation within spherical seeds (6mm) around those coordinates in over 11,000 fMRI studies, and then combined the identified co-activations to form the MACM output (Wu et al., 2022). Additionally, the program assigned a *Z*-score to each voxel, indicating the strength of the association between the given voxel and the seed coordinates.

1 http://www.brainmap.org/ale/
2 http://NeuroSynth.org/

3 Results

3.1 Selection results

In this study, 20,971 articles were retrieved and the retrieved articles were imported into EndNote X9 software for de-duplication, resulting in 14,391 articles. A total of 13 articles were selected for inclusion. The literature selection process is shown in Figure 1.

3.2 Data extraction results

Thirteen articles were published between 2011 and 2024, including 5 (38.46%) RCTs, 5 (38.46%) QEDs, and 3 (23.08%) CSSs. These 13 articles included a total of 425 participants with an average age ranging from 8.9 to 16.8 years old. Except for two studies (Jin, 2016; Qu et al., 2024), the remaining studies reported the gender of the participants. Among them, Herting and Nagel (2013) specifically explored the characteristics of brain activation in girls, while the proportion of girls in other studies ranged from 44.4% to 71.0%. The participants mainly came from the United States (Chaddock et al., 2012; Chaddock-Heyman et al., 2013; Davis et al., 2011; Herting and Nagel, 2013; Krafft et al., 2014; Sachs et al., 2017; Voss et al., 2011), China (Chen et al., 2011; Chen et al., 2016b; Jin, 2016; Qu et al., 2024; Zhu et al., 2021), and Canada (Metcalfe et al., 2016).

The included intervention studies mainly comprise acute interventions (Chen et al., 2011; Chen et al., 2016b; Metcalfe et al., 2016) and long-term interventions (Chaddock-Heyman et al., 2013; Davis et al., 2011; Jin, 2016; Krafft et al., 2014; Qu et al., 2024; Sachs et al., 2017; Zhu et al., 2021). Among them, five

TABLE 1 Basic characteristics of the included studies.

Included studies	Study design	Subject characteristics				Interventions/exposures and controls	Main results	
		Sample size	Age	Girls(%)	Nationality		Tasks (results)	Brain activation
Chen et al., 2011	QED	9	10	55.6%	CHN	One 30 min moderate intensity (60∼69% HRmax) power bike (SE) intervention vs. pre-intervention	Flanker (↑)	Re-organized (MNI)
Davis et al., 2011	RCT	E = 56 C = 60	7∼11	56.0%	USA	13 ± 1.6 weeks high intensity (166 ± 8 bpm) exercise (running games, jump rope, and modified basketball and soccer) (VE), 2 times/week, 20 min/time (520 min) vs. sedentary activities	Antisaccade (↑)	Re-organized (Talairach)
Voss et al., 2011	CSS	E = 18 C = 18	E = 9.8 ± 0.6 C = 9.9 ± 0.6	E = 55.6% C = 38.9%	USA	Higher aerobic group, 53.6 ± 5.6 VO_2 max vs. lower aerobic group, 37.0 ± 4.1 VO_2max	Flanker (↑)	Re-organized (MNI)
Chaddock et al., 2012	CSS	E = 14 C = 18	E = 9.7 ± 0.6 C = 10.1 ± 0.5	E = 64.3% C = 38.9%	USA	Higher aerobic group, 53.1 ± 4.5 VO_2 max vs. lower aerobic group, 36.6 ± 4.4 VO_2max	Flanker (↑)	Increased (MNI)
Chaddock-Heyman et al., 2013	RCT	E = 14 C = 9	E = 8.9 ± 0.7 C = 8.9 ± 0.4	E = 50.0% C = 66.7%	USA	36 weeks of moderate to high intensity intervention to improve cardiorespiratory fitness, muscle strength, and motor skills (SE), 5 times/week, 60min/time (10800min) vs. wait control	GO/NO GO (↑)	Decreased (MNI)
Herting and Nagel, 2013	CSS	E = 17 C = 17	E = 16.6 ± 0.8 C = 16.2 ± 0.8	E = 100.0% C = 100.0%	USA	Higher fitness group, ≥ 10h/week aerobic activities vs. lower fitness group, ≤ 1.5h/week aerobic activities	Lexical associative memory encoding (→)	Decreased (Talairach)
Krafft et al., 2014	RCT	E = 22 C = 17	E = 9.7 ± 0.8 C = 9.9 ± 0.9	E = 71.0% C = 58.0%	USA	32 weeks high (161 ± 9 bpm) aerobic exercise (SE), 7 times/week, 40min/time (8960min) vs. sedentary attention control	Antisaccade (↑) Flanker (↑)	Decreased (MNI) Increased (MNI)
Jin, 2016	QED	E = 14 C = 12	E = 10.1 ± 1.0 C = 11.5 ± 0.8	NA	CHN	11 weeks moderate intensity (60∼69% HR max) combined exercise program (fancy running ++ martial arts + fancy jumping rope) (VE), 4 times/week, 30min/time (1320min) vs. regular activities	2-back (↑)	Increased (MNI)
Chen et al., 2016b	QED	9	10	44.4%	CHN	One 30 min moderate intensity (60∼69% HRmax) power bike (SE) intervention vs. pre-intervention	2-back (↑)	Increased (MNI)
Metcalfe et al., 2016	QED	30	16.8 ± 1.4	57.0%	CAN	One 27min moderate to high (60∼80% HRmax) power bike (SE) intervention vs. pre-intervention	GO/NO GO (→)	Decreased (MNI)
Sachs et al., 2017	QED	E = 13 C = 17	E = 8.9 ± 0.6 C = 9.1 ± 0.5	E = 55.6% C = 4.0%	USA	2 years soccer (3 times/week) and swimming (2 times/week) exercise, 60min/time (VE) (31200 min) vs. daily activities	Stroop (↑)	Increased (MNI)
Zhu et al., 2021	RCT	E = 9 C = 8	E = 11.2 ± 1.2 C = 11.8 ± 0.9	E = 44.4% C = 50.0%	CHN	11 weeks moderate intensity (60–69% HR max) after-school exercise (running games, jump rope, martial arts) (VE), 4 times/week, 30min/time (1320 min) vs. no additional exercise	N-back (↑)	Increased (MNI)
Qu et al., 2024	RCT	E = 12 C = 12	NA	NA	CHN	11 weeks moderate intensity (60–69% HR max) aerobic exercise (fancy running + martial arts + fancy jumping rope) (VE) vs. regular activities	2-back (↑)	Increased (MNI)

E, experimental/exposure group; C, control group; NA, not applicable; RCT, randomized controlled trial; QED, quasi- experimental design; CSS, cross-sectional study; CHN, China; USA, United States; CAN, Canada; VE, variable exercise; SE, sustained exercise; HRmax, maximum heart rate; bpm, heartbeat rhythm; VO2max, maximum oxygen uptake; ↑ indicates improved cognitive task performance in the intervention/exposure group compared with the control group; → indicates that cognitive task performance was not significantly altered in the intervention/exposure group compared with the control group.

TABLE 2 RCT quality assessment results.

Included studies	Randomized methods	Blinding	Allocation concealment	Completeness of outcome data	Selective reporting of study results	Other biases
Davis et al., 2011	Unclear	Double-blind	Unclear	7 cases of missed visits	No	Unclear
Chaddock-Heyman et al., 2013	Unclear	Unclear	Unclear	9 cases of missed visits	No	Unclear
Krafft et al., 2014	Unclear	Unclear	Unclear	11 cases of missed visits	No	Unclear
Zhu et al., 2021	Unclear	Unclear	Unclear	9 cases of missed visits	No	Unclear
Qu et al., 2024	Unclear	Unclear	Unclear	2 cases of missed visits	No	Unclear

TABLE 3 QED quality assessment results.

Included studies	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	Total
Chen et al., 2011	2	2	2	2	0	1	2	0	NA	NA	NA	NA	11
Jin, 2016	2	2	2	2	0	1	2	0	2	2	2	2	19
Chen et al., 2016b	2	2	2	2	0	1	2	0	NA	NA	NA	NA	11
Metcalfe et al., 2016	2	2	2	2	0	1	2	0	NA	NA	NA	NA	11
Sachs et al., 2017	2	2	2	2	0	1	0	0	2	2	2	2	17

(1) the purpose of the study was clearly given; (2) the consistency of the included subjects; (3) the expected data collection; (4) the outcome indicators appropriately reflected the purpose of the study; (5) the objectivity of the evaluation of the outcome indicators; (6) the adequacy of the follow-up time; (7) the loss rate was less than 5%; (8) whether the sample size was estimated; (9) the appropriateness of the selection of the control group; (10) the synchronization of the control group; (11) the comparability of the baseline between groups; (12) the appropriateness of the statistical analysis; NA, not applicable.

TABLE 4 CSS quality assessment results.

Included studies	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Voss et al., 2011	①	①	③	③	①	③	①	③	③
Chaddock et al., 2012	①	①	③	③	①	①	①	③	③
Herting and Nagel, 2013	①	①	③	③	①	①	①	③	③

(1) Is the source of the information specified? (2) Are inclusion and exclusion criteria for the exposed and non-exposed groups listed or reference to previous publications? (3) Is the time period for identifying patients given? (4) Do subjective factors of the evaluator obscure other aspects of the study population? (5) Describes any assessment for quality assurance; (6) Explains the rationale for excluding any patients from the analysis; (7) Describes how confounding factors were evaluated and/or measures to control for confounding; (8) If possible, explains how missing data were handled in the analysis; (9) Summarizes the response rate of patients and the completeness of data collection; ①, yes; ②, no; ③, unclear.

studies (Chen et al., 2011; Chen et al., 2016b; Jin, 2016; Qu et al., 2024; Zhu et al., 2021) utilized moderate-intensity interventions, two studies (Davis et al., 2011; Krafft et al., 2014) applied high-intensity interventions, and two studies (Chaddock-Heyman et al., 2013; Metcalfe et al., 2016) adopted moderate-to- high-intensity interventions. The duration of acute interventions ranged from 27 to 30 minutes, while the duration of long-term interventions varied from 11 weeks to 2 years, with a total intervention time spanning from 520 to 31,200 minutes. Five studies (Chaddock-Heyman et al., 2013; Chen et al., 2011; Chen et al., 2016b; Krafft et al., 2014; Metcalfe et al., 2016) employed sustained exercise interventions aimed at improving cardiorespiratory health and aerobic fitness, while five studies (Davis et al., 2011; Jin, 2016; Qu et al., 2024; Sachs et al., 2017; Zhu et al., 2021) utilized variable exercise interventions focused on learning complex motor skills and enhancing agility and coordination. In addition, the included CSSs mainly categorized participants into high and low aerobic fitness groups based on maximal oxygen consumption (Chaddock et al., 2012; Voss et al., 2011) or the duration of aerobic exercise (Herting and Nagel, 2013).

FMRI tasks are mainly divided into three categories: inhibitory control, working memory, and memory encoding. Among them, the inhibitory control task paradigms adopted by researchers include Flanker, Antisaccade, GO/NO GO, and Stroop; the working memory task paradigm adopted by researchers is N-back; and the memory encoding task is Lexical associative memory encoding. Seven studies (53.85%) showed increased brain activation among participants; four studies (30.77%) showed decreased brain activation; and three studies (23.08%) showed re-organized of brain activation after the intervention. More detailed basic information on the included articles can be found in Table 1; for detailed results of the brain activation changes, please refer to Supplementary Material 1; the narrative review included in the study is attached in Supplementary Material 2.

3.3 Quality assessment results

There was no bias in the 5 RCTs to selectively report study results, and it is unclear whether other biases existed. However, only one study (Davis et al., 2011) reported a blinded strategy, no study reported randomized methods and allocation concealment methods, and all outcome data were incomplete, with a lost access sample between 2 and 11 cases (Table 2). The 5 QEDs included two (40.0%) non-randomized controlled designs and three (60.0%) single-group pre and post-test designs, of which the former had a mean quality assessment score of 18 and the latter had a mean quality assessment score of 11. The main reasons for the lower quality were the failure to use an assessor-blinded strategy for endpoint indicator evaluation and the failure to estimate the sample size (Table 3). All 3 CSSs reported on sources, subject selection criteria, quality assessment strategies, and control of confounders. However, it is not clear what time stage the subjects were identified, the subjective factors of confounding by the assessors, the explanation and manipulation of missing data, and the response rate of the participants (Table 4).

3.4 Frequency analysis of exercise induced activation of brain areas

In this study, frequency analysis of brain area activation outcomes was performed based on two dimensions of exercise-induced increased and decreased brain activation in children and adolescents. The results (Figure 2) showed that exercise induced increased or decreased activation in seven macroscopic brain areas, namely the frontal, parietal, temporal, occipital, limbic system, insula, and cerebellum, involving 23 brain areas. Specifically, exercise altered the activation status of the prefrontal, dorsolateral prefrontal, ventral lateral prefrontal, superior frontal gyrus, middle frontal gyrus, inferior frontal gyrus, precentral gyrus, supplementary motor area, orbitofrontal cortex, frontal pole and paracentral lobule in the frontal region; the parietal, superior parietal lobule, inferior parietal lobule, postcentral gyrus, and precuneus in the parietal region; the superior temporal gyrus in the temporal region; the middle occipital gyrus in the occipital region; and the cingulate gyrus, hippocampus, and parahippocampal gyrus in the limbic system.

In addition, this study performed a χ^2 test for the frequency of increased and decreased activation in macroscopic brain areas. Exercise induced increased activation in the occipital region and cerebellum, so it was not convenient to perform statistical analysis in this study. The results (Table 5) show that the frequency of exercise-evoked increased activation in the frontal ($\chi^2 = 10.093$, $P = 0.001$) and limbic system ($\chi^2 = 5.145$, $P = 0.023$) was significantly higher than the frequency of decreased activation.

3.5 ALE meta-analysis results

In this study, ALE meta-analysis was performed based on two dimensions of exercise-evoked increased and decreased brain activation, and the results (Table 6 and Figure 3) showed that the exercise intervention obtained six peak activation sites distributed on the left side of the brain, including four peak activation increased sites and two peak activation decreased sites, with a total volume of 2576 m^3 in the former activated brain area and 752 m^3 in the latter activated brain area. The four exercise- evoked clusters of increased activation included (1) brain areas dominated by the left medial frontal gyrus (89.7%), paracentral lobule (5.9%), and cingulate gyrus (4.4%) (BA6/31, X = 0, Y = 0, Z = 62); (2) brain areas dominated by the left precentral gyrus (56.3%) and middle frontal gyrus (43.8%) (BA8/9, X = −34, Y = 24, Z = 34); (3) brain areas dominated by the left middle frontal gyrus (85.7%) and inferior frontal gyrus (14.3%) (BA9/46, X = −46, Y = 24, Z = 24); and (4) left caudate nucleus (X = −6, Y = 22, Z = 2). The two clusters of exercise-evoked decreased activation included (1) brain areas on the left side dominated by the parahippocampal gyrus (73.8%), cerebellar apex (14.3%) and lingual gyrus (11.9%) (BA19/27/30, X = −14, Y = −42, Z = 0); (2) brain areas on the left side dominated by the posterior cingulate gyrus (52.0%) and cuneus (48.0%) (BA18/30/ 31, X = −22, Y = −68, Z = 18). In addition, in the MACM results (Table 7), this study found that the activation region dominated by the left intrafrontal gyrus overlapped with the brain function activation map in the NeuroSynth program ($Z = 33.11$), indicating that exercise can induce the enhancement of functional activation closely related to cognition.

3.6 The test of moderator variables

The results of frequency analysis of exercise-induced brain activation in children and adolescents (Figure 4) showed that: (1) The increased and decreased of whole- brain activation induced by different study designs were statistically significant ($P < 0.01$), among which the brain regions with enhanced activation in the QED experiment were significantly more than those with decreased activation; (2) The increased and decreased of whole-brain and frontal association area activation induced by different ages were statistically significant ($P < 0.01$), among which the brain regions with increased activation in whole-brain and frontal association area in children were significantly more than those with decreased activation; (3) The increased and decreased of whole-brain activation induced by different genders were statistically significant ($P < 0.01$), among which the brain regions with increased whole-brain activation induced by experiments with less than 50% female participants were significantly more than those with decreased activation; (4) The increased and decreased of whole-brain and frontal association area activation induced by different nationalities were statistically significant ($P < 0.01$), among which the brain regions with increased activation in whole-brain and frontal association area of Chinese participants were significantly more than those with decreased activation; (5) The increased and decreased of whole-brain and frontal association area activation induced by different cognitive tasks were statistically significant ($P < 0.01$), among which the brain regions with increased activation in whole-brain and frontal association area induced by working memory tasks were significantly more than those with decreased activation; (6) The increased and decreased of whole-brain and frontal association area activation induced by exercise intensity were statistically significant ($P < 0.01$), among which the brain regions with increased activation in whole-brain and frontal association area induced by moderate-intensity exercise were significantly more than those with decreased activation; (7) The increased and decreased of whole- brain and frontal association area activation induced by exercise types were

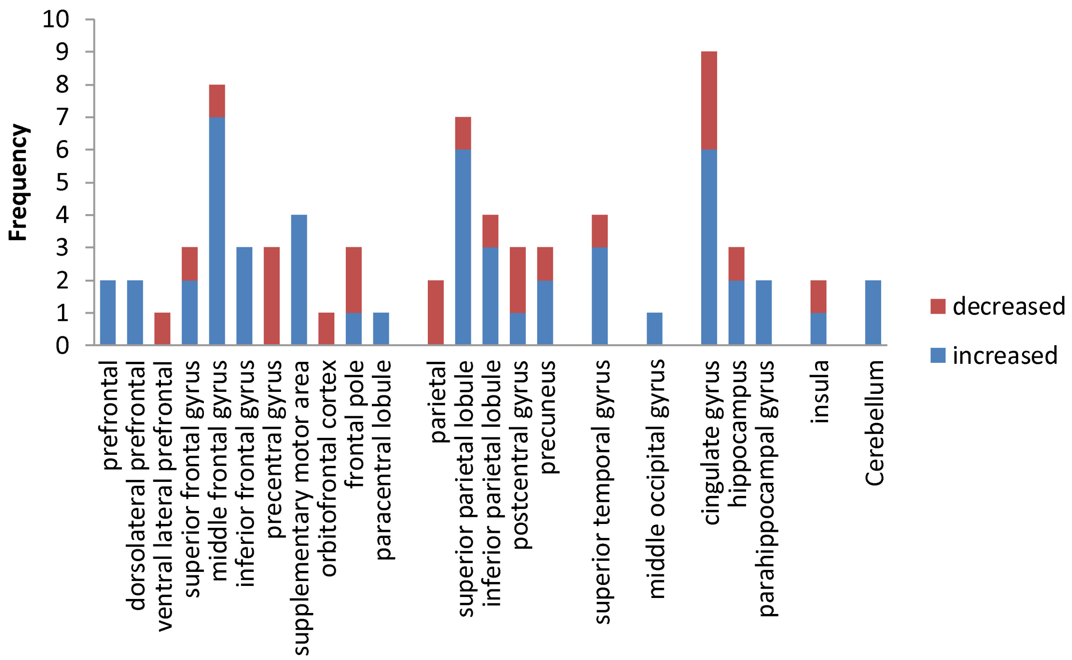


FIGURE 2
Frequency distribution of exercise-induced increased and decreased activation of brain areas in children and adolescents.

TABLE 5 Results of the χ2 test for exercise-induced changes in the activation status of macroscopic brain areas in children and adolescents.

Brain areas	Activate increased frequency	Activate decreased frequency	χ^2	*P*
Frontal	22	9	10.093	0.001
Parietal	12	7	2.632	0.105
Temporal	3	1	2.000	0.157
Limbic system	10	4	5.145	0.023
Insula	1	1	0.000	1.000

statistically significant ($P < 0.05$), among which the brain regions with increased activation in whole-brain and frontal association area induced by variable exercise were significantly more than those with decreased activation. In addition, this study has not found that the increased and decreased of whole-brain and frontal association area activation induced by exercise duration were statistically significant ($P > 0.05$).

The total intervention time contributed to 1.1% of the variability in the number of activated brain regions in the whole-brain during exercise interventions, and 16.2% of the variability in the frontal association areas (Figure 5). In other words, the longer the total intervention time, the greater the number of activated brain regions.

This study focuses on analyzing the differences in brain region activation induced by sustained and variable exercise. The results (Table 8) show that continuous exercise induced decreased activation in the left side of the brain areas dominated by the parahippocampal gyrus (50.0%), culmen (39.1%) and lingual gyrus (10.9%) (BA19/27/30, X = −14, Y = −42, Z = 0), with a volume of 840 m^3 of activated brain areas, while variable exercise induced increased activation in the left middle frontal gyrus (BA46, X = −46, Y = 24, Z = 24), with a volume of 592 m^3 of activated brain areas.

4 Discussion

4.1 Frontal association area dominate in exercise-induced brain activation

Based on the results of ALE meta-analysis, this study found increased and decreased exercise-induced brain activation and presence in the fMRI series of experiments, and the activation effect was more prominent in the frontal association area. Exercise altered the activation status of a series of brain regions in the frontal association area (intrafrontal gyrus, middle frontal gyrus, inferior frontal gyrus and precentral gyrus), parietal (cuneus), occipital (lingual gyrus), limbic system (cingulate gyrus and parahippocampal gyrus), striatum (caudate nucleus) and cerebellum. The activation volume of the frontal association area was 2057 m^3, accounting for 61.81% of the activation cluster volume. In addition, the activation of frontal association area showed increased effects, thus the results support the "extended frontoparietal integration theory" and the "neural efficiency hypothesis". Since the improvement of cognitive or behavioral tasks in humans is the result of the synergistic action of neurons in multiple brain areas (Popescu et al., 2009), the improvement of cognition or behavior due to exercise is also necessarily the result of improved functional connectivity in multiple brain areas. In addition, the results of the brain network analysis by Chen et al. (2016a) showed a significant positive correlation between the functional connectivity of the

TABLE 6 Activation cluster results from ALE meta-analysis.

Activation	Brain areas	BA areas	Hemisphere	Volume /m^3	Talairach Coordinate			ALE value (x 10^{-2})
					X	Y	Z	
Increased	89.7% intrafrontal gyrus / 5.9% paracentral lobule / 4.4% cingulate gyrus	BA6/31	Left	1064	0	0	62	1.11
	56.3% precentral gyrus/43.8% middle frontal gyrus	BA8/9	Left	616	−34	24	34	1.49
	caudate nucleus	caudate nucleus	Left	472	−6	22	2	1.27
	85.7% middle frontal gyrus/14.3% inferior frontal gyrus	BA9/46	Left	424	−46	24	24	1.15
Decreased	73.8% parahippocampal gyrus/14.3% cerebellar apex /11.9% lingual gyrus	BA19/27/30	Left	544	−14	−42	0	1.14
	52.0% posterior cingulate gyrus/48.0% cuneus	BA18/30/31	Left	208	−22	−68	18	0.94

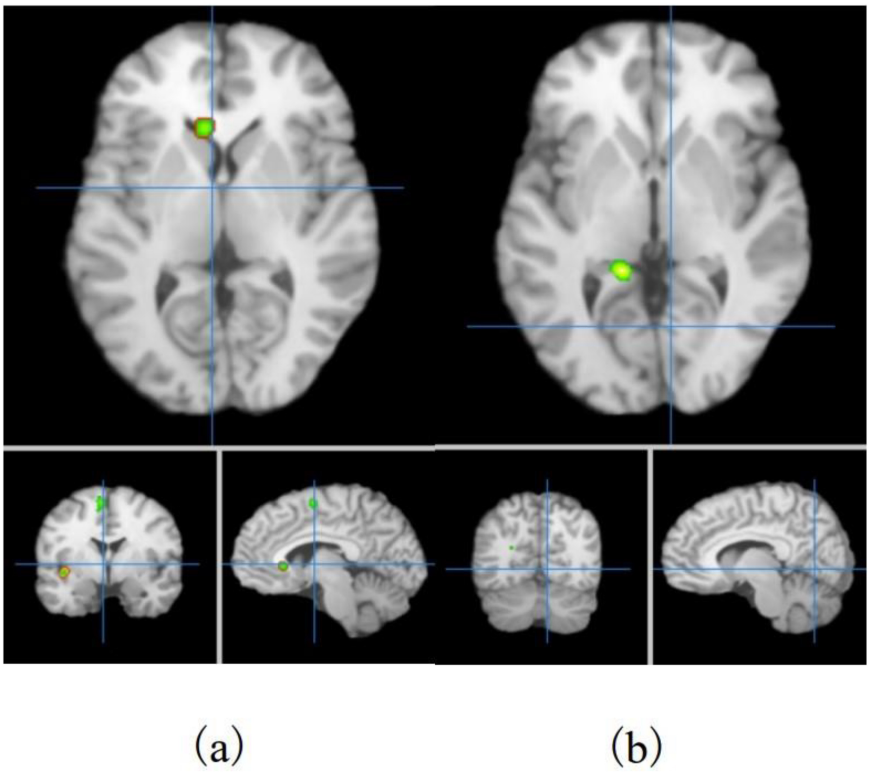
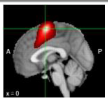
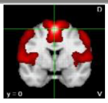
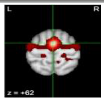
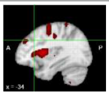
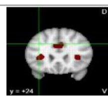
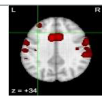
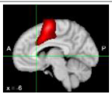
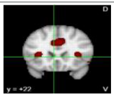
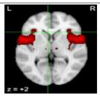
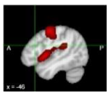
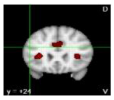
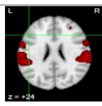
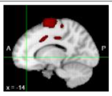
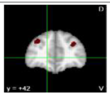
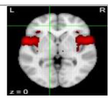
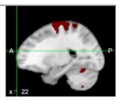
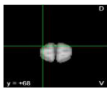
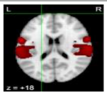


FIGURE 3
Distribution of exercise-induced increased **(a)** and decreased **(b)** activation brain areas in children and adolescents.

right inferior frontal gyrus-right cerebellum and 2-back task performance; Chen et al. (2017) showed that the functional connectivity of the right dorsolateral prefrontal-left cerebellum was significantly and negatively correlated with Flanker task performance. The above study further supports the results of our study.

Exercise-induced brain plasticity does not manifest only as a single increased or decreased activation, but rather as a coexistence of increased and decreased activation. The simultaneous presence of exercise-induced increased and decreased activation in brain areas in part suggests that exercise improves the efficiency of coordinated central nervous processing (Genç et al., 2018;

TABLE 7 The results of co-activation maps.

Brain areas	Hemisphere	Talairach Coordinate			*Z*-score
		X	Y	Z	
89.7% intrafrontal gyrus / 5.9% paracentral lobule / 4.4% cingulate gyrus	Left				33.11
56.3% precentral gyrus/43.8% middle frontal gyrus	Left				0.00
caudate nucleus	Left				0.00
85.7% middle frontal gyrus/14.3% inferior frontal gyrus	Left				0.00
73.8% parahippocampal gyrus/14.3% cerebellar apex /11.9% lingual gyrus	Left				0.00
52.0% posterior cingulate gyrus/48.0% cuneus	Left				0.00

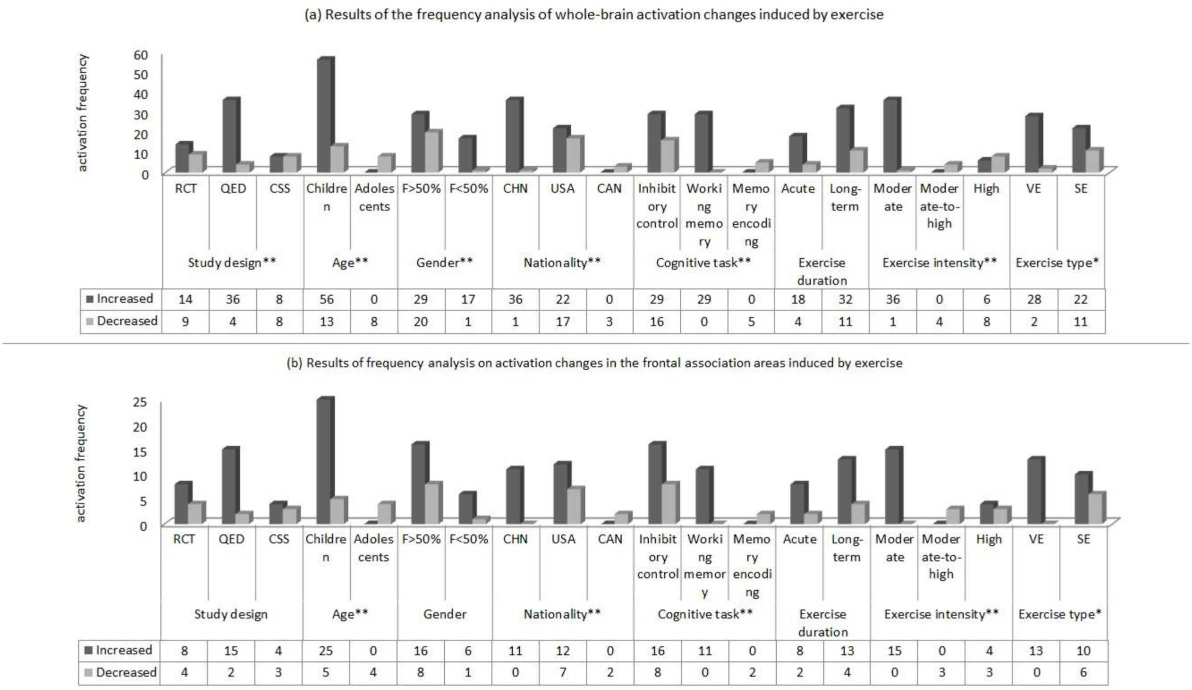


FIGURE 4
Results of frequency analysis on activation changes in the whole brain **(a)** and frontal association areas **(b)** of children and adolescents induced by exercise (Notes and Abbreviations: RCT, randomized controlled trial; QED, quasi-experimental design; CSS, cross-sectional study; F>50% indicates that the proportion of female participants exceeds 50%; F<50% indicates that the proportion of female participants is below 50%; CHN, China; USA, United States; CAN, Canada; VE, variable exercise; SE, sustained exercise; * indicates that $P < 0.05$; ** indicates that $P < 0.01$).

Guo et al., 2017). The dual processing model of cognitive control (Schneider and Shiffrin, 1977; Wei, 2019) states that acquired exercise can facilitate a shift from controlled processing that requires consciousness to automated processing that does not require specialized control, reducing the use of individual conscious resources and conserving central attention resources.

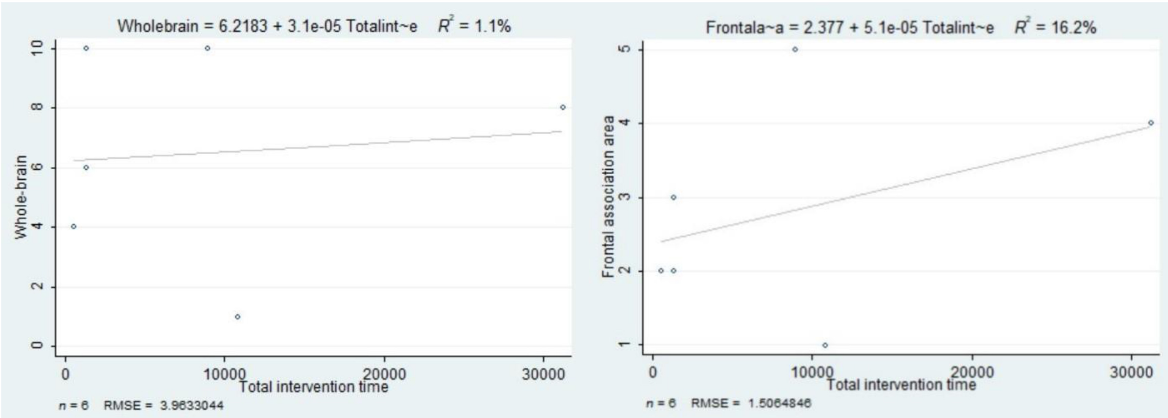


FIGURE 5
The association between total intervention time and the number of activated brain regions in the whole brain and frontal association areas.

TABLE 8 ALE meta-analysis activation cluster results for different exercise types.

Exercise types	Activation	Brain areas	BA areas	Hemisphere	Volume /m^3	Talairach Coordinate			ALE value (x 10^{-2})
						X	Y	Z	
Sustained exercise	Decreased	50.0% parahippocampal paracentral gyrus/39.1% culmen/10.9% lingual gyrus	BA19/27/30	Left	840	−14	−42	0	1.14
Variable exercise	Increased	Middle frontal gyrus	BA46	left	592	−46	24	24	1.15

Among the activation-enhancing brain areas, the activation in the frontal association area was more intensive. The frontal lobe is the most developed brain lobe in the body and is involved in higher cognitive functions such as language processing, number crunching, and working memory (Boisgueheneuc et al., 2006; Koyama et al., 2017) as well as playing a regulatory role in decision making and execution (Rushworth et al., 2004). Long-term exercise improves people's language processing and reading fluency (Scudder et al., 2014), number crunching and logical thinking (Haapala et al., 2017; Howie et al., 2015), executive function and academic performance (Fu and Fan, 2016), and these behavioral-level changes somewhat support the results of brain activation. In addition, groups that engage in long-term exercise have higher self-control (Fu and Liu, 2018; Yang, 2022) and a good self-control is important for planning and problem solving as well as program execution. However, exercise induces decreased activation of the parahippocampal gyrus and posterior cingulate gyrus during cognitive tasks in children and adolescents. The cingulate gyrus and the fronto-parietal association area are thought to scaffold human cognitive and thinking activities (Schneiders et al., 2011) and are involved in functions such as emotion, learning, and memory; the parahippocampal gyrus plays an important role in cognitive tasks such as spatial memory and navigation (Bohbot et al., 2015), and its decreased activation may be relevant to the fMRI experimental task. The cognitive task paradigm involved in their study hardly involves complex spatial memory extraction and storage, and therefore does not reflect the main functions of the above-mentioned brain areas.

4.2 The moderating variables of exercise-induced brain plasticity

4.2.1 Study design

This study found that in QED, the number of brain regions showing increased activation induced by exercise was significantly greater than the number showing decreased activation, indicating that the research design may have caused heterogeneity in the results of brain region activation. However, QED lacks random assignment, which cannot fully control research conditions, and there may be selection bias and other systematic biases, resulting in more interference from external factors and affecting the accuracy of causal inference. Therefore, it is recommended that future studies adopt more RCTs to explore the brain plasticity induced by exercise in children and adolescents, in order to improve the reliability of research results.

4.2.2 Characteristics of participants

Firstly, the number of brain regions activated by exercise in children is significantly greater than the number of those deactivated, and this result is not observed in adolescents. In terms of the development of executive control functions in the brain, Wang and Su (2006) have found that individuals generally reach adult levels in many standardized executive function tests around age 12. Zhao et al. (2015) have shown that younger children have a more significant advantage in terms of cognitive improvement induced by exercise, suggesting that exercise is more likely to induce brain plasticity in younger children. Furthermore, Wang et al. (2019) have also further confirmed this finding, revealing that exercise has positive promoting benefits for children, adolescents, and the elderly, but the effect size in the child population is significantly higher than that in other groups.

Secondly, in studies where girls make up less than 50%, exercise induces more activation enhancement in brain regions, while this result has not yet been found in studies where girls are less than 50%. The maturity of various regions of the female brain reaches its peak 2 to 4 years earlier than that of boys (Sabbatini, 1997), thus typically requiring more time for intervention to achieve positive benefits (Zhao et al., 2015). In addition, gender roles and expectations may affect an individual's psychological response to exercise. Sociocultural tendencies to encourage boys to participate more in exercise may lead to boys having a more positive psychological expectation for exercise, which could enhance brain activation after exercise.

Finally, this study found that exercise induced a significant increase in the number of activated brain regions among Chinese children and adolescents, with more activations than deactivations. This study has not yet found research on the differences in brain region activation induced by exercise among participants of different nationalities or ethnicities. The explanation for this finding may involve cultural differences, education systems, lifestyles, sample selection, research methods, and other aspects, but further research is needed to determine the specific reasons.

4.2.3 Cognitive task

This study found that exercise significantly increased the number of brain regions activated in the whole brain and frontal lobe association areas during working memory tasks, compared to a decrease. However, this finding was not reflected in inhibitory control and memory encoding tasks. Firstly, inhibitory control and working memory are sub-components of executive function. The former is the process of purposefully controlling an individual's habitual responses, while the latter is the process of managing and decoding new information in the cognitive process, while replacing old irrelevant information with new information (Shi et al., 2022). Therefore, in terms of task difficulty, working memory tasks are significantly more challenging than inhibitory control tasks, thus requiring a broader range of cognitive resources during working memory tasks. Secondly, only one study (Herting and Nagel, 2013) has used memory encoding tasks for research, which may limit the accuracy of the results, and we look forward to further exploration in subsequent studies.

4.2.4 Characteristics of exercise

Firstly, the number of brain regions activated by moderate-intensity exercise significantly exceeds the number of regions with reduced activation, a finding similar to previous studies exploring the relationship between exercise intensity and cognitive performance (Xie, 2020; Shi et al., 2022). For example, Xie (2020) compared the intervention effects of moderate and high-intensity exercise on children and adolescents' working memory, finding that moderate-intensity exercise has a positive intervention effect on both children and adolescents, while the intervention effect of high-intensity exercise is not significant, which may be related to the excessive fatigue induced by high-intensity exercise. Shi et al. (2022), based on a real exercise scenario, also presented similar results, showing that both acute and long-term interventions of moderate exercise are conducive to improving the executive functions of children and adolescents.

Secondly, although there is no statistical difference in the number of brain regions activated or deactivated by acute and long-term exercise, in long-term interventions, the longer the total intervention time, the more activation in the frontal association areas. Long-term exercise may promote the neuroplasticity of the brain, that is, the adaptive changes of the brain's structure and function to experience. The frontal lobe association areas are regions in the brain related to executive functions, decision-making, and complex cognitive tasks. Long-term exercise may enhance the neural connections and the efficiency of neural networks in these areas, thereby increasing their activation (Chaddock-Heyman et al., 2013). In addition, long-term exercise may be accompanied by individuals' psychological adaptation and habit formation to exercise, and this change in psychological state may affect brain activity, especially in the frontal lobe areas related to emotional regulation and motivation (Shi et al., 2023).

Finally, exercise-evoked brain plasticity during cognitive tasks in children and adolescents differed in exercise types, that is, sustained exercise evoked decreased activation of the parahippocampal gyrus, Culmen and lingual gyrus, whereas variable exercise evoked increased activation of the frontal middle gyrus. For sustained exercise, the results of this study were similar to a previous study (Metcalfe et al., 2016). Their findings showed that a single moderate-to-vigorous intensity power bike intervention induced decreased activation of the parahippocampal gyrus. Activation of the parahippocampal gyrus may be related to the exercise types chosen by the subjects; subjects who engage in long-term variable exercise such as basketball may have higher brain white matter volume in the parahippocampal gyrus areas (Shen et al., 2014), while participants who engage in long-term closed skill exercise such as diving have lower brain gray matter density in this area (Wei et al., 2009). In addition, the Culmen area of the cerebellum is important for maintaining body balance and coordination; while the lingual gyrus is responsible for receiving visual information and is involved in analyzing complex images and storing visual memories (Mendoza et al., 2011). Although Culmen and the lingual gyrus have some control over cognitive and thinking activities, this modulation is not as strong as in the frontal association area; therefore, the decreased activation in the above mentioned areas is a reflection of neural efficiency. For example, Wei et al. (2009) based on a voxel-based method of morphological analysis of the whole brain showed that the gray matter volumes in the right cerebellum and left lingual gyrus were much smaller in divers than in the average participants; Guo et al. (2017) compared the differences in brain area activation between table tennis players and normal participants when they were stimulated with the GO/NO GO task based on fMRI, and found that table tennis players had significantly decreased activation in the bilateral lingual gyrus. For variable exercise, the results of this study are similar to the results of previous ALE meta-analyses (Lou and Liu, 2020) on the activation state of the athlete's brain. The study included athletes engaged in open skills training in basketball, soccer, volleyball, tennis, badminton and field hockey and found that athletes had stronger activation in the middle frontal gyrus than controls in all cases. Thus, variable exercise is more conducive to plasticity in the frontal association area, which in turn is more conducive to promoting cognitive brain function benefits in participants.

4.3 Limitations of this study

Firstly, due to the limitation of search language, this study primarily searched for research in Chinese and English, potentially omitting relevant research findings that were published in other languages. Secondly, considering the limited number of original RCTs, this study included QEDs and CSSs in the ALE meta-analysis, which may interfere with the accuracy of the study results. Particularly in QEDs, there may be selection bias and systematic errors due to the lack of random assignment and the inability to fully control research conditions. Lastly, given the limited number of original studies, although this study explored relevant moderating variables, the number of original studies in some subgroups is relatively small, thus the results of this study should be interpreted with caution.

4.4 Implications for exercise intervention practice

This study found that variable exercise can induce more activation in the frontal associative areas, which serves as a reminder that in intervention practices, we should pay more attention to the moderating role of exercise types. Interventions should incorporate elements that promote variability to enhance the brain function of children and adolescents. Firstly, by adding key elements that promote variability in practice to the intervention, including environmental stimuli, interpersonal interactions, and complex tasks, the aim is to trigger cognitive challenges in children and adolescents and to enhance the activation of the frontal association area. In addition, it is becoming the norm for students in China to learn options based on their sport interests, and the benefits of different types of skills on brain plasticity and cognitive facilitation are different. Therefore, it is recommended that sports skill instruction incorporate the above elements into the design of learning and practice activities. By optimizing the teaching context, improving the teaching atmosphere, and providing complex tasks, both exercise interests are satisfied and the plasticity of the frontal association area is increased. Secondly, exercise methods that incorporate motor-cognitive dual-tasks can be adopted to improve the allocation of cognitive resources in children and adolescents during exercise and enhance the brain's engagement in cognitive tasks. The so-called motor-cognitive dual-task exercise refers to the form of exercise where cognitive, thinking, and decision-making tasks are performed during exercise. This type of exercise shares similarities with variable exercise, in that it involves cognitive participation amidst sustained repetitive movements, which may have a positive effect on promoting brain plasticity. Finally, exercise based on digital screens like Xbox shares similarities with variable exercise; the former offers a rich array of games that involve cognitive challenges, which has a positive significance for shaping the prefrontal cortex.

5 Conclusion

Exercise promotes improved brain cognitive task performance by inducing plasticity in the frontal association area. In view of the general characteristics of exercise-induced brain plasticity, this study was based on the "extended frontoparietal integration theory" and the "neural efficiency hypothesis", and found that the activation volume of the frontal association area accounted for 61.81% of the activation cluster volume induced by exercise based on ALE analysis. This study confirms that the frontal association area is a key site of exercise-induced brain plasticity. Additionally, the increase and decrease in the number of brain region activations induced by exercise exhibit differences in study design, age, gender, nationality, cognitive tasks, exercise intensity, duration, and type of exercise. Particularly, it was found that exercise induces differences in brain plasticity in children and adolescents based on the type of exercise. That is, sustained exercise induced a decrease in activation in the left parahippocampal gyrus, culmen, and lingual gyrus, while variable exercise induced an increase in activation in the left middle frontal gyrus. For exercise interventions, this study emphasizes that longer intervention times with moderate-intensity variable exercise can induce greater brain plasticity and exert a more active cognitive enhancement benefit.

Data availability statement

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

Author contributions

ZZ: Data curation, Methodology, Validation, Investigation, Visualization, Software, Writing – review & editing. PS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review and editing. KZ: Data curation, Investigation, Methodology, Project administration, Software, Visualization, Writing – review and editing. CL: Data curation, Investigation, Methodology, Software, Supervision, Visualization, Writing – review and editing. XF: Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing – review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of the article.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2024.1418803/full#supplementary-material

References

Bindman, A. B. (2017). The agency for healthcare research and quality and the development of a learning health care system. *JAMA Intern. Med.* 177, 909–910. doi: 10.1001/jamainternmed.2017.2589

Bohbot, V. D., Allen, J. J., Dagher, A., Dumoulin, S. O., Evans, A. C., Petrides, M., et al. (2015). Role of the parahippocampal cortex in memory for the configuration but not the identity of objects: Converging evidence from patients with selective thermal lesions and fMRI. *Front. Hum. Neurosci.* 9:431. doi: 10.3389/fnhum.2015

Boisgueheneuc, F. D., Levy, R., Volle, E., Seassau, M., Duffau, H., Kinkingnehun, S., et al. (2006). Functions of the left superior frontal gyrus in humans: A lesion study. *Brain* 129, 3315–3328. doi: 10.1093/brain/awl244

Cai, Q. T. (2014). *National core literacy*. Taipei: Higher Education and Culture Business Ltd, 162.

Carlén, M. (2017). What constitutes the prefrontal cortex? *Science* 358, 478–482. doi: 10.1126/science.aan8868

Chaddock, L., Erickson, K. I., Prakash, R. S., Voss, M. W., VanPatter, M., Pontifex, M. B., et al. (2012). A functional MRI investigation of the association between childhood aerobic fitness and neurocognitive control. *Biol. Psychol.* 89, 260–268. doi: 10.1016/j.biopsycho.2011.10.017

Chaddock-Heyman, L., Erickson, K. I., Voss, M. W., Knecht, A. M., Pontifex, M. B., Castelli, D. M., et al. (2013). The effects of physical activity on functional MRI activation associated with cognitive control in children: A randomized controlled intervention. *Front. Hum. Neurosci.* 7:72. doi: 10.3389/fnhum.2013.00072

Chen, A. G., Yin, H. C., Wang, J., Li, X. N., and Song, Z. (2011). The fMRI study of acute moderate exercise on children's executive function. *China Sports Sci.* 31, 35–40. doi: 10.16469/j.css.2011.10.005

Chen, A. G., Zhu, L. N., Jin, L., Xing, X., Wang, W., and Yan, J. (2016a). Effects of aerobic exercise on executive control and its brain network in deaf children. *Sports Sci.* 37, 94–101.

Chen, A. G., Zhu, L. N., Yan, J., and Yin, H. C. (2016b). Neural basis of working memory enhancement after acute aerobic exercise: fMRI study of preadolescent children. *Front. Psychol.* 7:1804. doi: 10.3389/fpsyg.2016.01804

Chen, A. G., Zhu, L. N., Xiong, X., and Li, Y. (2017). Acute aerobic exercise alters executive control network in preadolescent children. *Rev. Psicol. Dep.* 26, 0132–137.

Chen, X. M., Fu, T., Liu, C., Zhang, B., Fu, Y. F., Li, E. Z., et al. (2022). Working memory training-induced neuroplasticity: A spatio-temporal model of decreasing brain area distribution based on a series of fMRI experiments. *Adv. Psychol. Sci.* 30, 255–278.

Costantino, G., Montano, N., and Casazza, G. (2015). When should we change our clinical practice based on the results of a clinical study? Searching for evidence: PICOS and PubMed. *Intern. Emerg. Med.* 10, 525–527. doi: 10.1007/s11739-015-1225-5

Cui, L., Yin, H. C., Shen, Q. Q., and Zhu, L. N. (2019). Neural mechanisms by which exercise affects individual executive control: An ALE meta-analysis based on brain imaging studies. *J. Capit. Univers. Phys. Educ. Sports* 31, 370–374. doi: 10.14036/j cnki.cn11-4513.2019.04.016

Cumpston, M., Li, T., Page, M. J., Chandler, J., Welch, V. A., Higgins, J. P., et al. (2019). Updated guidance for trusted systematic reviews: A new edition of the Cochrane Handbook for Systematic Reviews of Interventions. *Cochr. Database Syst. Rev.* 10:ED000142. doi: 10.1002/14651858.ED000142

Davis, C. L., Tomporowski, P. D., McDowell, J. E., Austin, B. P., Miller, P. H., Yanasak, N. E., et al. (2011). Exercise improves executive function and achievement and alters brain activation in overweight children: A randomized, controlled trial. *Health Psychol.* 30:91. doi: 10.1037/a0021766

Eickhoff, S. B., Laird, A. R., Grefkes, C., Wang, L. E., Zilles, K., and Fox, P. T. (2009). Coordinate-based activation likelihood estimation meta-analysis of neuroimaging data: A random-effects approach based on empirical estimates of spatial uncertainty. *Hum. Brain Mapp.* 30, 2907–2926. doi: 10.1002/hbm.20718

Eimontaite, I., Goel, V., Raymont, V., Krueger, F., Schindler, I., and Grafman, J. (2018). Differential roles of polar orbital prefrontal cortex and parietal lobes in logical reasoning with neutral and negative emotional content. *Neuropsychologia* 119, 320–329. doi: 10.1016/jneuropsychologia.2018.05.014

Fu, J., and Fan, Y. R. (2016). An experimental study on the effects of different duration of moderate intensity physical exercise on executive function and academic performance of junior high school students. *Sports Sci.* 37, 110–116.

Fu, J., and Liu, S. L. (2018). An experimental study on the effects of different times of moderate-to- vigorous physical exercise on junior high school students' academic self-control and academic performance. *Sports Sci.* 39, 114–120.

Genç, E., Fraenz, C., Schlüter, C., Friedrich, P., Hossiep, R., Voelkle, M. C., et al. (2018). Diffusion markers of dendritic density and arborization in gray matter predict differences in intelligence. *Nat. Commun.* 9:1905. doi: 10.1038/ s41467-018-04268-8

Guo, Z., Li, A., and Yu, L. (2017). "Neural efficiency" of athletes' brain during visuo-spatial task: An fMRI study on table tennis players. *Front. Behav. Neurosci.* 11:72. doi: 10.3389/fnbeh.2017.00072

Gur, R. C., Butler, E. R., Moore, T. M., Rosen, A. F., Ruparel, K., Satterthwaite, T. D., et al. (2021). Structural and functional brain parameters related to cognitive performance across development: Replication and extension of the parieto-frontal integration theory in a single sample. *Cereb. Cortex* 31, 1444–1463. doi: 10.1093/ cercor/bhaa282

Haapala, E. A., Väistö, J., Lintu, N., Westgate, K., Ekelund, U., Poikkeus, A. M., et al. (2017). Physical activity and sedentary time in relation to academic achievement in children. *J. Sci. Med. Sport* 20, 583–589. doi: 10.1016/ j.jsams.2016.11.003

Heilmann, F., Weinberg, H., and Wollny, R. (2022). The impact of practicing open-vs. closed-skill sports on executive functions—A meta-analytic and systematic review with a focus on characteristics of sports. *Brain Sci.* 12:1071. doi: 10.3390/ brainsci12081071

Herting, M. M., and Nagel, B. J. (2013). Differences in brain activity during a verbal associative memory encoding task in high-and low-fit adolescents. *J. Cogn. Neurosci.* 25, 595–612. doi: 10.1162/jocn_a_00344

Howie, E. K., Schatz, J., and Pate, R. R. (2015). Acute effects of classroom exercise breaks on executive function and math performance: A dose-response study. *Res. Q. Exerc. Sport* 86, 217–224. doi: 10.1080/02701367.2015.1039892

Jin, L. (2016). *An fMRI study of the effect of "running + martial arts exercises + fancy jumping rope" on working memory of deaf children*. Yangzhou: Yangzhou University.

Jung, R. E., and Haier, R. J. (2007). The parieto-frontal integration theory (P-FIT) of intelligence: Converging neuroimaging evidence. *Behav. Brain Sci.* 30, 135–154. doi: 10.1017/S0140525X07001185

Kane, M. J., and Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychon. Bull. Rev.* 9, 637–671. doi: 10.3758/bf03196323

Koyama, M. S., O'Connor, D., Shehzad, Z., and Milham, M. P. (2017). Differential contributions of the middle frontal gyrus functional connectivity to literacy and numeracy. *Sci. Rep.* 7:17548. doi: 10.1038/s41598-017-17702-6

Krafft, C. E., Schwarz, N. F., Chi, L., Weinberger, A. L., Schaeffer, D. J., Pierce, J. E., et al. (2014). An 8-month randomized controlled exercise trial alters brain activation during cognitive tasks in overweight children. *Obesity* 22, 232–242. doi: 10.1002/oby. 20518

Lancaster, J. L., Tordesillas-Gutiérrez, D., Martinez, M., Salinas, F., Evans, A., Zilles, K., et al. (2007). Bias between MNI and Talairach coordinates analyzed using the ICBM-152 brain template. *Hum. Brain Mapp.* 28, 1194–1205. doi: 10.1002/hbm

Li, B., and Zhang, Y. (2023). Brain activation patterns in the executive function of children and adolescents after an exercise intervention. *Soc. Behav. Pers. Int. J.* 51, 1–9. doi: 10.2224/sbp.12628

Liu, J. Y. (2017). The 'dose-response' relationship between aerobic physical exercise and executive function in college students. *J. Beijing Sport Univers.* 40, 58–64. doi: 10.19582/j.cnki.11-3785/g8.2017.01.010

Lou, H., and Liu, P. (2020). The effect of exercise training on changes in functional plasticity in the brain of athletes: An ALE analysis based on fMRI studies. *China Sport Sci.* 40, 65–71. doi: 10.16469/j.css.202007008

Mansouri, F. A., Tanaka, K., and Buckley, M. J. (2009). Conflict-induced behavioural adjustment: A clue to the executive functions of the prefrontal cortex. *Nat. Rev. Neurosci.* 10, 141–152. doi: 10.1038/nrn2538

Meijer, A., Königs, M., Vermeulen, G. T., Visscher, C., Bosker, R. J., Hartman, E., et al. (2020). The effects of physical activity on brain structure and neurophysiological functioning in children: A systematic review and meta-analysis. *Dev. Cogn. Neurosci.* 45:100828. doi: 10.1016/j.dcn.2020.100828

Mendoza, J. E., Lingual, G., and Kreutzer, J. S. (2011). *Encyclopedia of clinical neuropsychology*. New York, NY: Springer, 1468.

Metcalfe, A. W. S., MacIntosh, B. J., Scavone, A., Ou, X., Korczak, D., and Goldstein, B. I. (2016). Effects of acute aerobic exercise on neural correlates of attention and inhibition in adolescents with bipolar disorder. *Transl. Psychiatry* 6:e814. doi: 10.1038/tp.2016

Pan, X. W. (2018). School-based implementation of the national curriculum: Overall rationale and direction. *Educ. Res. Monthly* 34, 73–80. doi: 10.16477/j.cnki.issn1674-23112018.08.009

Pesce, C., Croce, R., Ben-Soussan, T. D., Vazou, S., McCullick, B., Tomporowski, P. D., et al. (2019). Variability of practice as an interface between motor and cognitive development. *Int. J. Sport Exerc. Psychol.* 17, 133–152. doi: 10 1080/1612197X.2016.1223421

Popescu, A. T., Popa, D., and Paré, D. (2009). Coherent gamma oscillations couple the amygdala and striatum during learning. *Nat. Neurosci.* 12, 801–807. doi: 10.1038/nn 2305

Qu, H., Tang, H., Wang, L., Wang, W., Zhao, Y., Chen, A., et al. (2024). Effects on brain structural and functional in deaf children after aerobic exercise training: A pilot cluster randomized controlled study. *Int. J. Neurosci.* 568, 1–10. doi: 10.1080/00207454.2024 2341910

Robinson, J. L., Laird, A. R., Glahn, D. C., Lovallo, W. R., and Fox, P. T. (2010). Metaanalytic connectivity modeling: Delineating the functional connectivity of the human amygdala.Hum. *Brain Mapp.* 31, 173–184. doi: 10.1002/hbm.20854

Rushworth, M. F. S., Walton, M. E., Kennerley, S. W., and Bannerman, D. M. (2004). Action sets and decisions in the medial frontal cortex. *Trends Cogn. Sci.* 8, 410–417. doi: 10.1016/j.tics.2004.07.009

Sabbatini, R. M. (1997). Are there differences between the brains of males and females. *Brain Mind Online Magazine* 12:598.

Sachs, M., Kaplan, J., Der Sarkissian, A., and Habibi, A. (2017). Increased engagement of the cognitive control network associated with music training in children during an fMRI Stroop task. *PLoS One* 12:e0187254. doi: 10.1371/journal.pone.0187254

Schneider, W., and Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychol. Rev.* 84:1. doi: 10.1037/0033- 295X.84.1.1

Schneiders, J. A., Opitz, B., Krick, C. M., and Mecklinger, A. (2011). Separating intra-modal and across-modal training effects in visual working memory: An fMRI investigation. *Cereb. Cortex* 21, 2555–2564. doi: 10.1093/cercor/bhr037

Scudder, M. R., Federmeier, K. D., Raine, L. B., Direito, A., Boyd, J. K., and Hillman, C. H. (2014). The association between aerobic fitness and language processing in children: Implications for academic achievement. *Brain Cogn.* 87, 140–152. doi: 10.1016/j.bandc.2014.03.016

Shen, G. H., Zhang, J., Wang, H., Zeng, Y. F., and Du, X. X. (2014). Changes in brain white matter in college athletes: A magnetic resonance diffusion tensor imaging-based study. *J. East China Normal Univers.* 59, 94–101.

Shi, P., and Feng, X. (2022). Motor skills and cognitive benefits in children and adolescents: Relationship, mechanism and perspectives. *Front. Psychol.* 13:1017825. doi: 10.3389/fpsyg.2022.1017825

Shi, P., Tang, Y., Zhang, Z., Feng, X., and Li, C. (2022). Effect of physical exercise in real-world settings on executive Function of typical children and adolescents: A systematic review. *Brain Sci.* 12:1734. doi: 10.3390/brainsci12121734

Shi, P., Xin, F., Zhang, D. Y., Zha, X. L., Wang, W. C., Jin, T., et al. (2023). Theoretical exploration of the benefits of physical exercise in promoting executive function in children and adolescents. *J. Wuhan Inst. Phys. Educ.* 57, 75–83. doi: 10.15930/j.cnki.wtxb.2023.11.009

Slim, K., Nini, E., Forestier, D., Kwiatkowski, F., Panis, Y., and Chipponi, J. (2003). Methodological index for non-randomized studies (minors): Development and validation of a new instrument. *ANZ J. Surg.* 73, 712–716. doi: 10.1046/j.1445-2197.2003.02748.x

Teng, J. (2016). Core literacy for the 21st century: International perceptions and local reflections. *J. Teach. Educ.* 3, 103–110.

Valkenborghs, S. R., Noetel, M., Hillman, C. H., Nilsson, M., Smith, J. J., Ortega, F. B., et al. (2019). The impact of physical activity on brain structure and function in youth: A systematic review. *Pediatrics* 144:e20184032. doi: 10.1542/peds.2018-4032

Voss, M. W., Chaddock, L., Kim, J. S., VanPatter, M., Pontifex, M. B., Raine, L. B., et al. (2011). Aerobic fitness is associated with greater efficiency of the network underlying cognitive control in preadolescent children. *Neuroscience* 199, 166–176. doi: 10.1016/j.neuroscience.2011.10.009

Wang, J. F., Qi, C. Z., and Wei, X. N. (2019). A meta-analysis of the effects of physical activity on executive functions. *J. Capit. Univers. Phys. Educ. Sports* 31, 375–384. doi: 10.14036/j.cnki.cn11-4513.2019.04.017

Wang, S. Z., and Su, H. W. (2006). The relationship between executive function subcomponents and academic achievement. *Chin. J. Appl. Psychol.* 26, 187–192.

Wassenaar, T. M., Williamson, W., Johansen-Berg, H., Dawes, H., Roberts, N., Foster, C., et al. (2020). A critical evaluation of systematic reviews assessing the effect of chronic physical activity on academic achievement, cognition and the brain in children and adolescents: A systematic review. *Int. J. Behav. Nutr. Phys. Activ.* 17, 1–18. doi: 10.1186/s12966-020-00959-y

Wei, G., Luo, J., and Li, Y. (2009). Brain structure in diving players on MR imaging studied with voxel-based morphometry. *Prog. Nat. Sci.* 19, 1397–1402. doi: 10.1016/j pnsc.2008.12.009

Wei, Y. (2019). *An EEG study of neural efficiency of cognitive processing in different spatial tasks in table tennis players*. Shanghai: Shanghai University of Sport.

Welsh, M. C., Pennington, B. F., and Groisser, D. B. (1991). A normative-developmental study of executive function: A window on prefrontal function in children. *Dev. Neuropsychol.* 7, 131–149. doi: 10.1080/875656491095 40483

Wu, J., Xiao, W., Yip, J., Peng, L., Zheng, K., Takyi Bentil, O., et al. (2022). Effects of exercise on neural changes in inhibitory control: An ALE meta-analysis of fMRI studies. *Front. Hum. Neurosci.* 16:891095. doi: 10.3389/fnhum.2022.891095

Xie, C. (2020). A meta-analysis of the impact of different exercise intensities on children and adolescents' working memory. *Chin. J. Sch. Health* 41, 356–360. doi: 10.16835/j.cnki.1000-9817.2020.03.010

Yang, Y. (2022). *A study on the effects of different program sports interventions on middle school students' self-control and attention*. Yangzhou: Yangzhou University.

Zhao, X., Chen, L., Fu, L., and Maes, J. H. (2015). "Wesley says": A children's response inhibition playground training game yields preliminary evidence of transfer effects. *Front. Psychol.* 6:207. doi: 10.3389/fpsyg.2015.00207

Zhu, L., Xiong, X., Dong, X., Zhao, Y., Kawczyñski, A., Chen, A., et al. (2021). Working memory network plasticity after exercise intervention detected by task and resting-state functional MRI. *J. Sports Sci.* 39, 1621–1632. doi: 10.1080/02640414.2021.1891722

Zhu, N., Jacobs, D. R., Schreiner, P. J., Yaffe, K., Bryan, N., Launer, L. J., et al. (2014). Cardiorespiratory fitness and cognitive function in middle age: The CARDIA study. *Neurology* 82, 1339–1346. doi: 10.1212/WNL.0000000000000310

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 23 September 2024
DOI 10.3389/fpsyg.2024.1415448

Check for updates

OPEN ACCESS

EDITED BY
Yaira Barranco-Ruiz,
University of Granada, Spain

REVIEWED BY
Nuno Couto,
Polytechnic Institute of Santarém, Portugal
Samuel Honório,
Polytechnic Institute of Castelo Branco, Portugal
Antonio Cicchella,
University of Bologna, Italy

*CORRESPONDENCE
Hao-Ming Yan
✉ 17608026885@163.com

RECEIVED 10 April 2024
ACCEPTED 09 September 2024
PUBLISHED 23 September 2024

CITATION
Yan H-M, Huang P, Chen R and Wang Y-C (2024) The relationship between physical activity and mental health of middle school students: the chain mediating role of negative emotions and self-efficacy.
Front. Psychol. 15:1415448.
doi: 10.3389/fpsyg.2024.1415448

The relationship between physical activity and mental health of middle school students: the chain mediating role of negative emotions and self-efficacy

Hao-Ming Yan[1]*, Ping Huang[2], Rui Chen[3] and Yi-Cheng Wang[4]

[1]Physical Education Academy (Gymnastics Academy), Chengdu Sport University, Chengdu, China, [2]Chengdu Railway Middle School Liren Branch, Chengdu, China, [3]Institute of Sports Training, Chengdu Sport University, Chengdu, China, [4]Dagang Shanggulin Primary School, Tianjin, China

Objective: To explore the relationship between mental health and physical activity (PA) in middle school students, and examining the roles of negative emotions and self-efficacy in the relationship.

Methods: Data from 1,134 Chinese middle school students (50.2% females, 49.8% males; $M_{age} = 15.18$, $SD_{age} = 2.00$) were collected using the Physical Activity Rating Scale (PARS-3), Positive and Negative Affect Scale (PANAS), General Self-Efficacy Scale (GSES), and Middle School Student Mental Health Scale (MSSMHS).

Results: (1) There is a significant positive correlation between PA and mental health ($r = 0.16$, $p < 0.01$), and the direct path of PA on mental health is significant ($t = 2.101$, $p < 0.01$). (2) PA negatively predicts negative emotions ($r = -0.12$, $p < 0.01$), and is significantly positively correlated with self-efficacy ($r = 0.24$, $p < 0.01$). Negative emotions negatively predict self-efficacy ($r = -0.23$, $p < 0.01$) and mental health ($r = -0.67$, $p < 0.01$). Self-efficacy positively predicts mental health ($r = 0.30$, $p < 0.01$). (3) Negative emotions and self-efficacy play a significant mediating role between PA and mental health. The mediating effect includes three paths: PA → negative emotion → mental health (effect value: 0.130); PA → self-efficacy → mental health (effect size: 0.052); PA → negative emotions → self-efficacy → mental health (effect size: 0.006).

Conclusion: PA among middle school students can indirectly affect mental health through negative emotions and self-efficacy. Middle school students should be encouraged to participate in PA to reduce their negative emotions and increase their self-efficacy, thus improving their mental health.

KEYWORDS

physical activity, negative emotion, self-efficacy, middle school student, chain mediation effect

1 Introduction

Mental health issues pose a significant challenge to global public health (World Health Organization, 2020). This is particularly concerning for adolescents, as they experience a high prevalence of mental health problems (Carter et al., 2015). Frequent occurrences of mental health problems among middle school students can often lead to security incidents on campus.

Because of their underdeveloped cognitive abilities and restricted problem-solving capabilities, these students might have a higher likelihood of participating in unlawful activities, posing a threat to campus security and societal harmony (Aebi et al., 2014). Meanwhile, mental health problems of secondary school students are also closely related to risky behaviors such as self-harm and suicide (Murdock et al., 2023). Research shows that PA is beneficial to improving mental health (Gmmash et al., 2023). However, many teachers and parents sill ignore PA, the curriculum reform has not achieved the goal of promoting students' physical and mental health as hoped by the Chinese government (Meng et al., 2021), and the severity of mental health problems among middle school students is escalating (Wu et al., 2022).

PA is good for people's mental health. PA reduces inflammation through several different processes (inflammation, cytokines, toll-like receptors, adipose tissue, and vagal tone), which can help to improve the health of people with mood disorders, and consequently mental health (Mikkelsen et al., 2017). Empirical studies have demonstrated that PA has a positive effect on the mental health of individuals across all age groups. Surveys conducted during the novel coronavirus pandemic have shown that appropriate PA during isolation can help reduce anxiety and depressive symptoms and enhance well-being in children, thereby improving mental health (Zhao et al., 2023). In addition, research with adolescents has shown that participation in moderate to high-level PA reduces their vulnerability to potential mental health problems and protects against poor mental health, preventing mental health problems (Rodríguez-Romo et al., 2022). Similarly, research with adults suggests that participating in PA can promote mental health by reducing the prevalence, incidence, and duration of mental disorders (Herbert, 2022). Engaging in PA, either solo or within a group, can improve social ties and provide support for older adults while positively influencing their mental health (Seino et al., 2019). Regular PA has been shown to have numerous benefits for middle school students. Nonetheless, research that clearly demonstrates how PA positively influences the mental health of middle school students remains insufficient.

Owing to significant academic stress, middle school students in China frequently experience prolonged periods of negative emotions, including feelings of depression and tension (Ma et al., 2024). In the long run, it could negatively impact mental health, contributing to the onset and exacerbation of mental illnesses and disorders (Iasiello et al., 2019; Jayasankar et al., 2022). Negative emotions can significantly predict mental health problems such as anxiety disorders, depressive symptoms, and problem behaviors (Ramadan et al., 2023). Higher levels of negative emotions can lead to distressing experiences and May interact with negative personality traits such as neuroticism, further damaging an individual's mental health (Karreman et al., 2013). Individuals who frequently experience negative emotions tend to have lower work efficiency (Xie et al., 2023), reduced life satisfaction (Barlow et al., 2023), difficulties in problem-solving and coping (Yu et al., 2021), and poorer physical and mental health (Lopez and Denny, 2019). Furthermore, one must not overlook the impact of self-efficacy on the mental health of students in middle school. Self-efficacy is closely related to various areas of human practice (Puozzo and Audrin, 2021). Improving self-efficacy in middle school students can aid in alleviating academic stress, minimizing the adverse effects associated with academic pressures and burnout (Chen et al., 2024; Fu et al., 2023), and aid in diminishing symptoms such as depression and anxiety (Tonga et al., 2020). Therefore, self-efficacy plays a crucial role in the mental health of adolescents (Dupéré et al., 2012); when their self-efficacy is low, the risk of encountering mental health issues rises significantly (Yan et al., 2021). Earlier studies have demonstrated that PA positively influences the reduction of negative emotions and enhances self-efficacy (Fathy et al., 2022; Tikac et al., 2021).

The strength and wisdom of young people are vital for the progress of a nation. Simultaneously, the execution of my nation's "Outline for Building a Strong Sports Nation" alongside the "National Fitness Plan (2021–2025)" and various other policies has made it crucial to explore effective strategies for improving the mental health of middle school students, which is now a significant subject within the realm of youth education in my country. Consequently, further research is needed to confirm and enhance our understanding of how PA improves mental health. While numerous studies have investigated the relationship between mental health and PA, the majority have concentrated on college students, middle-aged adults, and older adults. However, there is a lack of research on the interconnections and underlying mechanisms between PA and mental health in middle school students. Hence, this study constructed a mediation model of the intrinsic mechanism between PA and mental health (Figure 1), aiming to further explore the relationship between PA and the mental health of middle school students, and provide a theoretical basis for promoting the mental health of middle school students.

In summary, this study proposes the following hypothesis:

> *H1*: PA has a positive impact on the mental health of middle school students.
>
> *H2*: Negative emotions play a mediating role between PA and mental health.
>
> *H3*: Self-efficacy acts as a mediator between PA and mental health.
>
> *H4*: Participation in PA influences mental health by mediating the chain effect of negative emotions and self-efficacy.

Figure 1 depicts the model that represents the interplay among these four variables.

2 Methods

2.1 Participants and procedures

A total of 1,182 students in grades 7 through 12 were sampled from five middle schools in Chengdu, Sichuan Province, through facilitated cluster sampling. In this study, the author team engaged with the school principal and the class teacher in person, clarified the objective of the survey to both the principal and the teacher, and carried out the survey in the classroom following the approval from the principal and class teacher. The questionnaire was first introduced to the students by professionals and informed consent was obtained, and then distributed and collected by professionals with the assistance of class teachers. The data collection period for the questionnaire survey was from February 2024 to March 2024. To ensure data quality, clear identification criteria were established to eliminate invalid

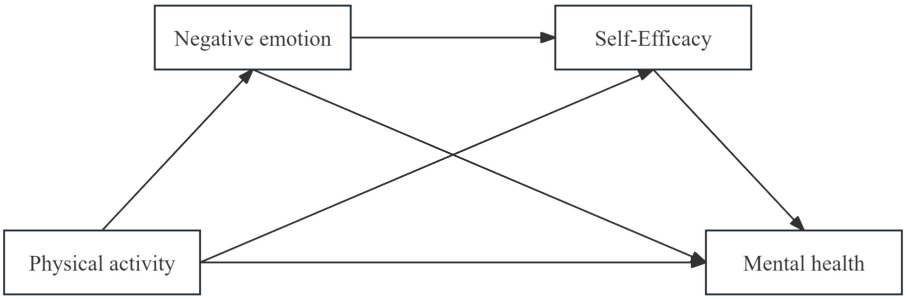


FIGURE 1
Hypothetical model.

questionnaires. The identification criteria for invalid questionnaires included contradictory answers, repetitive filling of relevant characters, and unanswered questions. As a result, 48 invalid questionnaires were excluded, and a total of 1,134 valid questionnaires were collected, yielding an effective rate of 95.9%. Among the valid respondents, 565 were boys (49.8%) and 569 were girls (50.2%). Furthermore, 616 respondents were aged 12–15 (54.3%), while 518 were aged 16–19 (45.7%), the mean age is 15.18 years old and the SD = 2.00. This study obtained ethical approval from Chengdu Sport University (Approval No. CTYLL2024003) and obtained consent from the participating schools and students.

2.2 Measuring tools

2.2.1 Physical Activity Rating Scale

The PA status of the research subjects was evaluated using the Chinese version of the physical activity scale revised by Liang (1994). The evaluation was based on three indicators: intensity, frequency, and duration. Each item was quantified using the 5-point Likert scoring method. Intensity and frequency were scored from 1 to 5, indicating weak to strong, while time was scored from 0 to 4, indicating weak to strong. The quantification of PA score was calculated as "intensity × time × frequency." Higher scores indicate higher levels of PA. In this survey, the Cronbach's alpha coefficient of the scale was 0.75.

2.2.2 Positive and Negative Affect Scale

The Positive and Negative Emotions Scale, revised by Chen and Zhang (2004), was used to assess the subjects' emotional state. The scale consists of two dimensions, positive and negative emotions, and the negative emotion dimension has 10 entries (e.g., "upset," "fearful," and "hostile"), and this study only used the negative emotion dimension scale to assess the participants' negative emotions levels. The scale was scored using a five-point Likert scale (1 = almost none, 2 = comparatively little, 3 = moderately much, 4 = comparatively much, 5 = extremely much). Higher scores on the negative affect subscale indicate that participants have more negative affect. In this survey, the Cronbach's alpha coefficient for the negative affect subscale of the scale was 0.87.

2.2.3 General Self-Efficacy Scale

The General Self-Efficacy Scale translated and revised by Wang et al. (2001) was used, which consists of 10 items (e.g., "I can always solve problems if I try my best," "I am confident that I can cope effectively with how things come up unexpectedly "). A 4-point Likert scale score was used for quantification (1 = not at all true, 2 = somewhat true, 3 = mostly true, 4 = completely true), with higher scores representing greater perceived self-efficacy on the individual's part. In this survey, the Cronbach's alpha coefficient of the scale was 0.90.

2.2.4 Middle School Student Mental Health Scale

The Middle School Student Mental Health Scale, developed by Wang et al. (1997), was used to assess the mental health of Chinese secondary school students based on their cultural characteristics and behavioral tendencies. The scale consists of 60 entries categorized into 10 dimensions, including obsessive-compulsive disorder (e.g., "I have to double-check my homework"), paranoia (e.g., "I always think differently from other people"), hostility (e.g., "I fight with other people"), interpersonal tension and sensitivity (e.g., "I feel that other people are not kind to me"), depression (e.g., "I feel that there is no hope in my future"), anxiety (e.g., "I feel tense or get nervous easily"), academic stress (e.g., "I feel that I have a heavy academic load"), maladjustment (e.g., "I feel uncomfortable with my current school life"), emotional instability (e.g., "I have good and bad moods"), and psychological imbalance (e.g., "I feel sad when my classmates do better than me in exams"). A five-point Likert scale was used (5 = none, 4 = mild, 3 = moderate, 2 = severe, 1 = very severe), with lower scores indicating poorer mental health and more serious mental health problems among participants. In this survey, the Cronbach's alpha coefficient of the scale was 0.97.

3 Data analysis

In order to examine any potential common method deviation, the researchers implemented the Harman single factor method (Podsakoff et al., 2003). The results showed: KMO = 0.97, which produced 13 factors with eigenvalues greater than 1, and a maximum factor variance explained of 30.68%, which is less than the general test of 40%, indicating that there was no significant common method bias in this study. SPSS 27 statistical software was utilized to perform common method deviation testing, description, and correlation analysis. To conduct questionnaire data entry, statistical analysis, and sequential chain mediation effect testing, we utilized the SPSS macro program Process 3.5 plug-in (Model 6) and the Bootstrap method.

The PROCESS macro program was employed to analyze the impact of the chain mediation model (Model 6).

4 Research results

4.1 Descriptive statistics and correlation analysis

The results of the study showed that the average score of PA in the sample was 28.04 ± 22.55, the average score of negative emotion was 19.90 ± 6.91, the average score of self-efficacy was 25.30 ± 6.18, and the average score of mental health was 251.73 ± 37.73 (Table 1).

The Pearson correlation analysis of all research variables in this study is shown in Table 2. PA has a weak but statistically significant negative correlation with negative emotions ($r = -0.12$, $p < 0.01$), indicating that more participation in PA can eliminate negative emotions. PA has a weak positive correlation with self-efficacy ($r = 0.24$, $p < 0.01$), which means that more participation in PA is conducive to the improvement of self-efficacy. PA has a weak positive correlation with mental health ($r = 0.16$, $p < 0.01$), suggesting participating in more PA is beneficial to mental health; negative emotions have a weak negative correlation with self-efficacy ($r = -0.23$, $p < 0.01$), demonstrating that individuals with high levels of negative emotions have low levels of self-efficacy; negative emotions are negatively correlated with mental health ($r = -0.67$, $p < 0.01$), showing that individuals with high levels of negative emotions have more serious mental health problems; self-efficacy is related to mental health is positively correlated ($r = 0.30$, $p < 0.01$), manifesting that individuals with high levels of self-efficacy have a higher level of mental health.

TABLE 1 Descriptive statistics between variables.

Scale/subscale	*M*	SD
1. Physical activity	28.04	22.55
2. Negative emotion	19.90	6.91
3. Self-efficacy	25.30	6.18
4. Mental health	251.73	37.73
4.1. Obsessive-compulsive disorder	24.07	3.87
4.2. Paranoia	25.68	4.25
4.3. Hostility	26.34	4.46
4.4. Interpersonal tension and sensitivity	25.39	4.43
4.5. Depression	25.30	4.78
4.6. Anxiety	24.97	5.03
4.7. Academic stress	23.93	5.17
4.8. Maladjustment	25.54	4.24
4.9. Emotional instability	24.17	4.53
4.10. Psychological imbalance	26.34	3.66

TABLE 2 Results of correlation analysis between variables.

Variable	1	2	3	4
1. Physical activity	1			
2. Negative emotion	−0.12**	1		
3. Self-efficacy	0.24**	−0.23**	1	
4. Mental health	0.16**	−0.67**	0.30**	1

**$p < 0.01$.

4.2 The chain mediating role of mental health, PA, negative emotions and self-efficacy between mental health and PA

In order to conduct additional exploration into the influence of PA on the mental health of middle school pupils, control variables such as gender and age were taken into account. The dependent variable was mental health, while PA was treated as the independent variable. Negative emotions and self-efficacy were used as mediating variables. The mediation effect test was conducted using Hayes' compiled SPSS macro program, employing Bootstrap method (Hayes, 2017). Model 6 was applied for the model test, with a sample size of 5,000 and a confidence interval of 95%.

Table 3 provides the outcomes of the regression analysis. Mental health is positively and significantly influenced by engaging in PA ($\beta = 0.266$, $p < 0.001$), whereas negative emotions are negatively and significantly affected ($\beta = -0.038$, $p < 0.001$). When self-efficacy is considered as a dependent variable with PA and negative emotions as predictors, PA ($\beta = 0.059$, $p < 0.001$) plays a vital positive role, while negative emotions ($\beta = -0.185$, $p < 0.001$) assume a significant negative role. Furthermore, when mental health is predicted using PA, negative emotions, and self-efficacy, both PA ($\beta = 0.078$, $p < 0.001$) and self-efficacy ($\beta = 0.887$, $p < 0.001$) demonstrate significant positive effects, with negative emotions ($\beta = -0.061$, $p < 0.001$) showcasing a strong negative impact.

Table 4 and Figure 2 contain the findings of the analysis conducted on the mediation effect. The value of the total effect is 0.266, and the 95% confidence interval excludes 0, signifying a significant total effect. On the other hand, the direct effect value is 0.078, and the 95% confidence interval does not encompass 0, indicating that PA significantly affects mental health directly. Additionally, the total indirect effect value is 0.188, 95% CI [0.123, 0.255], implying noteworthy mediating effects of negative emotions and self-efficacy between mental health and PA. The mediation effect of the variables negative emotions and mental health consists of three pathways: the indirect effect 1 (effect value 0.130, CI [0.069, 0.193]) is formed by the path of engaging in PA → experiencing negative emotions → achieving mental health, showing a substantial independent impact of negative emotions. The path of PA → enhancing self-efficacy → improving mental health creates an indirect effect 2 (effect value 0.052, CI [0.029, 0.077]), signifying a significant independent mediating effect of self-efficacy. Furthermore, the path of PA → triggering negative emotions → promoting self-efficacy → enhancing mental health demonstrates an indirect effect 3 (effect value 0.006, CI [0.003, 0.011]), revealing a noteworthy mediating effect of negative emotions → self-efficacy. The ratios of the three indirect effects to the total effect were 48.87, 19.55, and

TABLE 3 Regression analysis of variable relationships in the mediation model.

Regression equation		Overall fit coefficient			Regression coefficient significance	
Outcome variable	Predictor variable	*R*	R2	*F*	β	*t*
Negative emotion	Physical activity	0.123	0.015	17.358	−0.038	−4.167***
Self-efficacy	Physical activity	0.317	0.101	63.282	0.059	7.595***
	Negative emotion				−0.185	−7.303***
Mental health	Physical activity	0.690	0.476	341.709	0.078	2.101**
	Negative emotion				−3.452	−28.452***
	Self-efficacy				0.887	6.360***
Mental health	Physical activity	0.159	0.025	29.459	0.266	5.428***

***$p < 0.001$.

TABLE 4 Analysis of the mediating effect of mental health and PA.

Direct effect	Effect size	Boot SE	95% confidence interval		Relative mediation effect
			LLCI	ULCI	
Total effect	0.266	0.049	0.170	0.363	100%
Direct effect	0.078	0.038	0.005	0.151	29.30%
Total indirect effect	0.188	0.034	0.123	0.255	70.68%
Indirect effect 1	0.130	0.031	0.069	0.193	48.87%
Indirect effect 2	0.052	0.012	0.029	0.077	19.55%
Indirect effect 3	0.006	0.002	0.003	0.011	2.26%

2.26%, respectively. The independent mediating effect of negative emotions had the highest ratio to the total indirect effect.

5 Discussion

Students' mental health is as important as their physical health and is closely related to campus safety, family harmony, and social stability. Improving the mental health of middle school students is now a pressing issue in both education and society as a whole. This study explored the correlation between middle school students' engagement in PA and their mental health, while also examining the mediating effects of negative emotions and self-efficacy. The study's findings show that PA can predict mental health both directly and positively. Additionally, PA can indirectly forecast mental health through the independent mediating effects of negative emotions and self-efficacy, as well as through the combined chain mediating effect of both factors. These results carry significant implications for enhancing the mental health of middle school students.

5.1 The impact of PA on the mental health of middle school students

Data analysis conducted in this study showed that there is a direct relationship between the extent to which secondary school students participate in PA and their mental health. This finding is consistent with the originally-proposed hypothesis. The results of our study align with those of prior research, demonstrating a direct link between the engagement of high school students in PA and their mental health. Boosting students' involvement in PA could potentially enhance their mental health (Molcho et al., 2021). Therefore, Hypothesis H1 is confirmed. A study conducted by researchers in China discovered that incorporating music into PA can help foster a positive classroom environment, improve students' flexibility in coping with psychological challenges, steer students toward healthier psychological inclinations, and ultimately support the mental health of students (Liu, 2024). Enhancing PA levels May also aid in decreasing the general abnormal rate of mental health and easing psychological issues (Dong and Dou, 2023). At the same time, research by Western scholars has also confirmed that PA is beneficial to mental health. PA helps individuals have a more positive emotional response to events and allows individuals to maintain an objective and optimistic attitude toward life (Catalino and Fredrickson, 2011). Furthermore, participation in PA can improve students' mental health and well-being by increasing their ability to cope with life challenges and setbacks (Malagodi et al., 2024). Participation in sports also promotes positive emotions, self-esteem, and academic performance in adolescents (Rasmussen and Laumann, 2013). In addition, habitual PA are beneficial to brain development and help improve language expression, understanding and cognitive performance (Herting and Chu, 2017). These benefits contribute to the promotion of mental health and overall quality among middle school students. Therefore, middle school students should develop and maintain good PA habits, as PA is an important intervention to alleviate mental health problems when they occur (Klemmer et al., 2023).

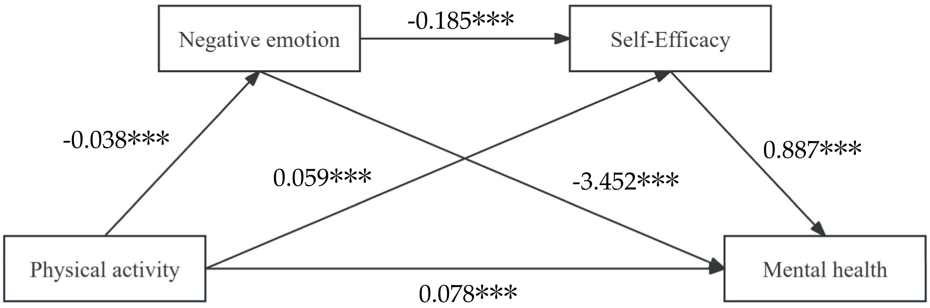


FIGURE 2
Chain mediation model diagram of negative emotions and self-efficacy. ****p* < 0.001.

5.2 The mediating role of negative emotions between PA and mental health

According to this research, it has been discovered that the connection between the mental health of middle school students and PA is mediated by negative emotions. Put simply, engaging in PA helps enhance the mental health of middle school students by diminishing negative emotions. Hypothesis H2 has been confirmed, as supported by prior research. Previous studies have consistently demonstrated that PA play a crucial role in improving mental health by effectively reducing negative emotions (Li J. et al., 2023; Li L. et al., 2023). Research by Chinese scholars shows that sitting for long periods of time will enhance negative emotions such as anxiety and stress among middle school students (Zou et al., 2023), affect the emotional flexibility of middle school students, and then affect mental health (Zhang et al., 2020). Conversely, PA can promote mental health by improving symptoms of depression and stress (Rong et al., 2024). Research by Western scholars has also prove PA can assist individuals in managing their emotional regulation deficiencies, alleviating the enduring negative impact of stressors, and facilitating the elimination of negative emotions (Bernstein and McNally, 2017). This reduction in negative emotions can lead to heightened positive emotional states among students, fostering feelings of cheerfulness, energy, and satisfaction (Reitsema et al., 2023). In summary, PA can enhance students' attention control, emotional control, life satisfaction, and overall physical and mental health. Moreover, based on physiological theory, engaging in PA can boost activation in the individual's prefrontal cortex, fortify functional connections across different brain regions, and enhance the flexibility of emotion regulation pathways and nodes, ultimately diminishing the perception of negative emotions and bolstering emotional control (Wang et al., 2024). As a result, it is essential to promote involvement in PA for middle school students during their educational journey in order to reduce negative emotions and improve mental health.

5.3 The mediating role of self-efficacy between PA and mental health

The findings indicate that self-efficacy plays a mediating role between PA and mental health, thus confirming Hypothesis 3. This finding is consistent with previous research (Guo and Jiang, 2023; Jia et al., 2022). This study confirms that PA has a positive predictive effect on middle school students' self-efficacy; self-efficacy has a positive predictive effect on mental health. Studies conducted by Chinese researchers show that adolescents who engage regularly in PA show marked improvements in both social and expressive abilities compared to their peers who are inactive (Li J. et al., 2023; Li L. et al., 2023). Such improvements in social interaction and expression are critical in bolstering self-regulation skills, which, in turn, contribute significantly to higher self-efficacy (Li, 2023). Additionally, participation in PA fosters greater perseverance and consistency of interest among adolescents, which further enhances their self-efficacy (Yu et al., 2024). Studies have shown that individuals with high self-efficacy have stronger psychological flexibility, higher levels of self-admission, self-control, and self-worth (Qin et al., 2023). Interacting with teammates during PA serves to expand adolescents' cognitive horizons, promote intellectual development, and improve adaptability. These interactions make them more cheerful, energetic, and positive in their outlook, providing a conducive environment for better mental health. Studies conducted by Western researchers support the finding that middle school students' PA is strongly linked to their life satisfaction as well as their physical and mental health (Zullig and White, 2011). Additionally, self-efficacy has been identified as a significant factor in the connection between PA and mental health (Paxton et al., 2010). At the same time, individuals with high self-efficacy have lower prevalence of depression, higher happiness, and higher levels of mental health (Mak et al., 2011; Paredes et al., 2021).

5.4 The chain mediating role of negative emotions and self-efficacy between PA and mental health

The research provided evidence that self-efficacy and negative emotions play a vital role as mediators between PA and mental health. Hypothesis 4 was validated by the results. It was discovered in this study that negative emotions negatively impact self-efficacy, and both factors were identified as crucial determinants of mental health (Hu et al., 2023; Zhang et al., 2024). Research indicates that individuals possessing high levels of self-efficacy are capable of effectively managing and diminishing the expression of their negative emotions (Caro and Popovac, 2021). On the other hand, those who often experience negative emotions are likely to exhibit unrealistic feelings of happiness, set overly emotional goals, show a limited ability to regulate their emotions, and have low self-efficacy. This, consequently, can impact mental health by contributing to mood disorders, behavioral issues, and potentially leading to psychiatric disorders (Clauss et al., 2019). Engaging in PA fosters the development of a positive mindset, mitigates negative emotions, boosts self-esteem, and enhances one's ability to cope with life's challenges, thereby promoting a higher sense of self-efficacy and a stronger self-identity (Akdeniz and Kaştan, 2023; De Marco et al., 2023). These improvements also support better interpersonal relationships and social adaptability (Haoran et al., 2023). Consequently, individuals who participate in PA tend to exhibit superior mental health, heightened physical and psychological resilience, and a reduced susceptibility to mental health issues such as anxiety and depression. In conclusion, for middle school students, the connection between PA and mental health should take into account the intermediary impact of feelings of negativity and self-belief.

6 Implications

The present research investigates the impact of PA on the mental health of middle school students, focusing on negative emotions and self-efficacy. It offers both theoretical and practical insights for parents and teachers on how to effectively promote the mental health of such students. The study further highlights the significant role of negative emotions in the impact of PA on mental health. Therefore, parents and teachers should actively engage in daily communication with children to understand their emotional experiences. Providing children with adequate opportunities for PA can help alleviate negative emotions and ensure their mental health. Furthermore, the study also emphasizes the importance of self-efficacy in the relationship between PA and mental health. Parents, teachers, and coaches should provide more encouragement, praise, and affirmation to students engaging in PA. This will help students gain more experience in PA and achieve higher levels of sports mastery. Additionally, it will enhance their verbal persuasion abilities and increase their level of self-efficacy (Peura et al., 2021). To begin, parents and teachers should address their negative attitudes toward PA. In China, many parents and teachers believe that PA consume students' energy and time, hinder their learning progress, and impact their academic performance. This perception needs to be changed, and they should develop a correct understanding of the positive impact of PA on students' physical and mental health. By adopting a supportive and understanding approach, while minimizing rejection, parents and teachers can encourage students to participate in PA. During sports, it is important for parents, teachers, and coaches to actively listen to the needs of students, while also observing and guiding their emotions. They should also take advantage of the unique characteristics of various sports to foster the comprehensive development of students' personalities, will qualities, temperaments, and spiritual qualities. In sports such as basketball and football, which rely on teamwork and communication, students May experience negative emotions due to coordination errors. In these situations, it is important for parents, teachers, and coaches to actively guide them. This guidance will help students learn how to regulate their uncomfortable emotions while interacting with their peers and develop and enhance their social skills (Fan, 2023). In the field of future education, it is crucial to prioritize the enhancement of mental health among middle school students. One effective approach to achieve this is by encouraging their active engagement in specific PA that are tailored to meet their needs and promote overall well-being. By taking this approach, we can systematically improve their mental health and contribute to their overall development. By recognizing the significance of mental health and implementing targeted PA programs, we can foster a positive learning environment for middle school students, ensuring their long-term academic success.

7 Limitations and strengths

This study has several limitations. Firstly, the sample source is limited to Sichuan Province, China, and has not been expanded to include a wider geographical area. China's vast territory encompasses significant economic and cultural variations among different regions. Middle school students in these regions May experience varying academic pressures and have different attitudes toward learning and sports. Therefore, future research should take into account factors such as city, family income, and academic pressure. Secondly, as this study is a cross-sectional study, several influencing factors have not yet been explored or considered. Additionally, due to time and resource constraints, the questionnaire used in this study primarily employed the Likert scale to gather responses, without conducting more in-depth interviews. Future research could aim to conduct a more comprehensive investigation of middle school students' PA and mental conditions, by employing a focused one-to-one model, in order to enhance the depth and breadth of the study. The research subjects of this study are all selected from China, which is important as China's educational system, educational concepts, and culture are significant contextual factors. Therefore, future research should aim to broaden the scope of the survey and strive to obtain samples from different countries in order to conduct more comprehensive research. In conclusion, while this study acknowledges certain limitations, it effectively establishes that negative emotions and self-efficacy serve as mediating factors between PA and mental health. This relationship enhances our understanding of the mechanisms affecting the mental health of middle school students, offering both theoretical insights and empirical data. Furthermore, the findings of this research offer creative approaches for both educators and parents aiming to enhance mental health results for middle school students, while also laying the groundwork for additional investigation into mental health topics concerning this age group.

8 Conclusion

PA has a notable impact on the mental health of middle school students. The relationship between PA and mental health affects the levels of negative emotion and self-efficacy in these students, both directly and indirectly. This implies that engaging in more PA is linked to decreased negative emotions and increased self-efficacy, resulting in overall improvements in mental health. Consequently, focusing on reducing negative emotions and fostering self-efficacy can be beneficial for enhancing the mental health of middle school students.

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 humans were approved by Sports Training College of Chengdu Sports University. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

H-MY: Writing – original draft, Writing – review & editing. PH: Investigation, Writing – review & editing. RC: Data curation, Writing – review & editing. Y-CW: Data curation, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by the Chengdu Sport University "14th Five-Year Plan" Scientific Research Innovation Team Project (23CXTD05).

Acknowledgments

All of our researchers would like to express our sincere gratitude to the subjects who participated in this study.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1415448/full#supplementary-material

References

Aebi, M., Giger, J., Plattner, B., Metzke, C. W., and Steinhausen, H. C. (2014). Problem coping skills, psychosocial adversities and mental health problems in children and adolescents as predictors of criminal outcomes in young adulthood. *Eur. Child Adolesc. Psychiatry* 23, 283–293. doi: 10.1007/s00787-013-0458-y

Akdeniz, Ş., and Kaştan, Ö. (2023). Perceived benefit of yoga among adults who have practiced yoga for a long time: a qualitative study. *Bio Psycho Soc. Med.* 17:19. doi: 10.1186/s13030-023-00276-3

Barlow, M. A., Willroth, E. C., Wrosch, C., John, O. P., and Mauss, I. B. (2023). When daily emotions spill into life satisfaction: Age differences in emotion globalizing. *Psychol. Aging* 38, 644–655. doi: 10.1037/pag0000771

Bernstein, E. E., and McNally, R. J. (2017). Acute aerobic exercise helps overcome emotion regulation deficits. *Cognit. Emot.* 31, 834–843. doi: 10.1080/02699931.2016.1168284

Caro, C., and Popovac, M. (2021). Gaming when things get tough? Examining how emotion regulation and coping self-efficacy influence gaming during difficult life situations. *Games Cult.* 16, 611–631. doi: 10.1177/1555412020944622

Carter, T., Guo, B., Turner, D., Morres, I., Khalil, E., Brighton, E., et al. (2015). Preferred intensity exercise for adolescents receiving treatment for depression: a pragmatic randomised controlled trial. *BMC Psychiatry* 15, 247–212. doi: 10.1186/s12888-015-0638-z

Catalino, L. I., and Fredrickson, B. L. (2011). A Tuesday in the life of a flourisher: the role of positive emotional reactivity in optimal mental health. *Emotion* 11, 938–950. doi: 10.1037/a0024889

Chen, Y., Li, C., Cao, L., and Liu, S. (2024). The effects of self-efficacy, academic stress, and learning behaviors on self-regulated learning in blended learning among middle school students. *Educ. Inf. Technol.* doi: 10.1007/s10639-024-12821-w

Chen, W. F., and Zhang, J. X. (2004). Structure and validity of the Chinese version of the positive/negative affect scale. Chinese. *J. Ment. Health* 11:763-765+759. doi: 10.3321/j.issn:1000-6729.2004.11.003

Clauss, K., Bardeen, J. R., Benfer, N., and Fergus, T. A. (2019). The interactive effect of happiness emotion goals and emotion regulation self-efficacy on anxiety and depression. *J. Cogn. Psychother.* 33, 97–105. doi: 10.1891/0889-8391.33.2.97

De Marco, J. C. P., Dias, D. T., Gonzaga, I., Duek, V. P., Farias, G. O., Martins, C. R., et al. (2023). Effects of teasing in physical education classes, self-efficacy, and physical activity on adolescents' self-esteem. *Psicol. Educ.* 29, 185–191. doi: 10.5093/psed2023a13

Dong, R. B., and Dou, K. Y. (2023). Changes in physical activity level of adolescents and its relationship with mental health during regular COVID-19 prevention and control. *Brain Behav.* 13:e3116. doi: 10.1002/brb3.3116

Dupéré, V., Leventhal, T., and Vitaro, F. (2012). Neighborhood processes, self-efficacy, and adolescent mental health. *J. Health Soc. Behav.* 53, 183–198. doi: 10.1177/0022146512442676

Fan, X. (2023). Accountability in the evaluation of teacher effectiveness: views of teachers and administrators. *Educ. Assess. Eval. Account.* 35, 585–611.

Fathy, K. A., Allah Jasim, M. A., Jawad, H. H., Aljuboory, D. S., Al Majidi, A. R. J., Rashed, Y. A., et al. (2022). Moderating effect of physical activity between the relation of psychological resilience and negative emotions of university students in Iraq. *J. Sport Psychol.* 31, 142–152. Available at: https://mail.rpd-online.com/index.php/rpd/article/view/725

Fu, W., Li, Y., Liu, Y., Li, D., Wang, G., Liu, Y., et al. (2023). The influence of different physical activity amounts on learning burnout in adolescents: the mediating effect of self-efficacy. *Front. Psychol.* 14:1089570. doi: 10.3389/fpsyg.2023.1089570

Gmmash, A., Alonazi, A., Almaddah, M., Alkhateeb, A., Sabir, O., and Alqabbani, S. (2023). Influence of an 8-week exercise program on physical, emotional, and mental health in Saudi adolescents: a pilot study. *Medicina* 59:883. doi: 10.3390/medicina59050883

Guo, M., and Jiang, S. (2023). Structural modeling of EFL/ESL teachers' physical activity, mental health, psychological well-being, and self-efficacy. *BMC Psychol.* 11:343. doi: 10.1186/s40359-023-01383-0

Haoran, S., Tianci, L., Hanwen, C., Baole, T., Yiran, C., and Yan, J. (2023). The impact of basketball on the social adjustment of Chinese middle school students: the chain mediating role of interpersonal relationships and self-identity. *Front. Psychol.* 14:1205760. doi: 10.3389/fpsyg.2023.1205760

Hayes, A. F. (2017). Introduction to mediation, moderation, and conditional process analysis: A regression-based approach. Guilford Publications.

Herbert, C. (2022). Enhancing mental health, well-being and active lifestyles of university students by means of physical activity and exercise research programs. *Front. Public Health* 10:849093. doi: 10.3389/fpubh.2022.849093

Herting, M. M., and Chu, X. (2017). Exercise, cognition, and the adolescent brain. *Birth Defects Res.* 109, 1672–1679. doi: 10.1002/bdr2.1178

Hu, D., Kalokerinos, E. K., and Tamir, M. (2023). Flexibility or instability? Emotion goal dynamics and mental health. *Emotion* 24, 1078–1091. doi: 10.1037/emo0001318

Iasiello, M. A., JosephKeyes, C. L. M., and Cochrane, E. M. (2019). Positive mental health as a predictor of recovery from mental illness. *J. Affect. Disord.* 251, 227–230. doi: 10.1016/j.jad.2019.03.065

Jayasankar, P., Manjunatha, N., Rao, G. N., Gururaj, G., Varghese, M., Benegal, V., et al. (2022). Epidemiology of common mental disorders: results from "national mental health survey" of India, 2016. *Indian J. Psychiatry* 64, 13–19. doi: 10.4103/indianjpsychiatry.indianjpsychiatry_865_21

Jia, J., Song, L., and Li, L. (2022). Effects of physical activity on mental health and general self-efficacy of city residents in COVID-19. *J. Sport Psychol.* 31, 57–66. Available at: http://mail.rpd-online.com/index.php/rpd/article/view/647

Karreman, A., Van Assen, M. A., and Bekker, M. H. (2013). Intensity of positive and negative emotions: explaining the association between personality and depressive symptoms. *Personal. Individ. Differ.* 54, 214–220. doi: 10.1016/j.paid.2012.08.040

Klemmer, B., Kinnafick, F. E., Spray, C., and Chater, A. M. (2023). The effectiveness of structured sport and exercise interventions in enhancing the mental health of adolescents with mild to moderate mental health problems: a systematic review. *Int. Rev. Sport Exerc. Psychol.* 1–24. doi: 10.1080/1750984X.2023.2266823

Li, B. (2023). The relationship between physical exercise and self-efficacy of college students and the mediating role of emotional self-regulation. *J. Sport Psychol.* 32, 241–249. doi: 10.2224/sbp.13098

Li, J., Jiang, X., and Huang, Z. (2023). Exercise intervention and improvement of negative emotions in children: A Meta-analysis. *BMC Pediatr.* 23:411. doi: 10.1186/s12887-023-04247-z

Li, L., Li, Y., and Mei, Z. (2023). A low degree of physical activity adherence in college students: analyzing the impact of interpersonal skills on exercise adherence in college students. *J. Racial Ethn. Health Disparities*, 1–10. doi: 10.1007/s40615-023-01747-7

Liang, D. Q. (1994). Stress level and its relation with physical activity in higher education. *Chin. Ment. Health J.* 8, 5–6.

Liu, Z. (2024). Music teaching curriculum integrates physical exercise to regulate Students' mental health. *J. Sport Psychol.* 33, 426–435. Available at: https://rpd-online.com/index.php/rpd/article/view/1590

Lopez, R. B., and Denny, B. T. (2019). Negative affect mediates the relationship between use of emotion regulation strategies and general health in college-aged students. *Personal. Individ. Differ.* 151:109529. doi: 10.1016/j.paid.2019.109529

Ma, A., Tan, S., Chen, J., and Lou, H. (2024). Stress events and stress symptoms in Chinese secondary school students: gender and academic year characteristics of the relationship[J]. *Front. Public Health* 12:1360907. doi: 10.3389/fpubh.2024.1360907

Mak, W. W., Ng, I. S., and Wong, C. C. (2011). Resilience: enhancing well-being through the positive cognitive triad. *J. Couns. Psychol.* 58, 610–617. doi: 10.1037/a0025195

Malagodi, F., Dommett, E. J., Findon, J. L., and Gardner, B. (2024). Physical activity interventions to improve mental health and wellbeing in university students in the UK: a service mapping study. *Ment. Health Phys. Act.* 26:100563. doi: 10.1016/j.mhpa.2023.100563

Meng, X., Horrell, A., McMillan, P., and Chai, G. (2021). 'Health First'and curriculum reform in China: the experiences of physical education teachers in one city. *Eur. Phys. Educ. Rev.* 27, 595–612. doi: 10.1177/1356336X20977886

Mikkelsen, K., Stojanovska, L., Polenakovic, M., Bosevski, M., and Apostolopoulos, V. (2017). Exercise and mental health. *Maturitas* 106, 48–56. doi: 10.1016/j.maturitas.2017.09.003

Molcho, M., Gavin, A., and Goodwin, D. (2021). Levels of physical activity and mental health in adolescents in Ireland. *Int. J. Environ. Res. Public Health* 18:1713. doi: 10.3390/ijerph18041713

Murdock, A. R., Rogers, M. L., Jackson, T. L., Monteiro, K., and Chambers, L. C. (2023). Mental health status of Rhode Island middle school and high school students before versus during the COVID-19 pandemic. *J. Sch. Health* 94, 489–500. doi: 10.1111/josh.13424

Paredes, M. R., Apaolaza, V., Fernandez-Robin, C., Hartmann, P., and Yañez-Martinez, D. (2021). The impact of the COVID-19 pandemic on subjective mental well-being: the interplay of perceived threat, future anxiety and resilience. *Personal. Individ. Differ.* 170:110455. doi: 10.1016/j.paid.2020.110455

Paxton, R. J., Motl, R. W., Aylward, A., and Nigg, C. R. (2010). Physical activity and quality of life—the complementary influence of self-efficacy for physical activity and mental health difficulties. *Int. J. Behav. Med.* 17, 255–263. doi: 10.1007/s12529-010-9086-9

Peura, P., Aro, T., Räikkönen, E., Viholainen, H., Koponen, T., Usher, E. L., et al. (2021). Trajectories of change in reading self-efficacy: a longitudinal analysis of self-efficacy and its sources. *Contemp. Educ. Psychol.* 64:101947. doi: 10.1016/j.cedpsych.2021.101947

Podsakoff, P. M., MacKenzie, S. B., Lee, J. Y., and Podsakoff, N. P. (2003). Common method biases in behavioral research: a critical review of the literature and recommended remedies. *J. Appl. Psychol.* 88, 879–903. doi: 10.1037/0021-9010.88.5.879

Puozzo, I. C., and Audrin, C. (2021). Improving self-efficacy and creative self-efficacy to foster creativity and learning in schools. *Think. Skills Creat.* 42:100966. doi: 10.1016/j.tsc.2021.100966

Qin, L. L., Peng, J., Shu, M. L., Liao, X. Y., Gong, H. J., Luo, B. A., et al. (2023). The fully mediating role of psychological resilience between self-efficacy and mental health: evidence from the study of college students during the COVID-19 pandemic. *Healthcare* 11:420. doi: 10.3390/healthcare11030420

Ramadan, R., Randell, A., Lavoie, S., Gao, C. X., Manrique, P. C., Anderson, R., et al. (2023). Empirical evidence for climate concerns, negative emotions and climate-related mental ill-health in young people: a sco** review. *Early Interv. Psychiatry* 17, 537–563. doi: 10.1111/eip.13374

Rasmussen, M., and Laumann, K. (2013). The academic and psychological benefits of exercise in healthy children and adolescents. *Eur. J. Psychol. Educ.* 28, 945–962. doi: 10.1007/s10212-012-0148-z

Reitsema, A. M., Jeronimus, B. F., van Dijk, M., Ceulemans, E., van Roekel, E., Kuppens, P., et al. (2023). Distinguishing dimensions of emotion dynamics across 12 emotions in adolescents' daily lives. *Emotion* 23, 1549–1561. doi: 10.1037/emo0001173

Rodríguez-Romo, G., Acebes-Sánchez, J., García-Merino, S., Garrido-Muñoz, M., Blanco-García, C., and Diez-Vega, I. (2022). Physical activity and mental health in undergraduate students. *Int. J. Environ. Res. Public Health* 20:195. doi: 10.3390/ijerph20010195

Rong, F., Li, X., Jia, L., Liu, J., Li, S., Zhang, Z., et al. (2024). Substitutions of physical activity and sedentary behavior with negative emotions and sex difference among college students. *Psychol. Sport Exerc.* 72:102605. doi: 10.1016/j.psychsport.2024.102605

Seino, S., Kitamura, A., Tomine, Y., Tanaka, I., Nishi, M., Taniguchi, Y. U., et al. (2019). Exercise arrangement is associated with physical and mental health in older adults. *Med. Sci. Sports Exerc.* 51, 1146–1153. doi: 10.1249/MSS.0000000000001884

Tikac, G., Unal, A., and Altug, F. (2021). Regular exercise improves the levels of self-efficacy, self-esteem and body awareness of young adults. *J. Sports Med. Phys. Fitness* 62, 157–161. doi: 10.23736/S0022-4707.21.12143-7

Tonga, J. B., Eilertsen, D. E., Solem, I. K. L., Arnevik, E. A., Korsnes, M. S., and Ulstein, I. D. (2020). Effect of self-efficacy on quality of life in people with mild cognitive impairment and mild dementia: the mediating roles of depression and anxiety. *Am. J. Alzheimers Dis. Other Dement.* 35:153331751988526. doi: 10.1177/1533317519885264

Wang, C. K., Hu, Z. Y., and Liu, Y. (2001). Research on the reliability and validity of the general self-efficacy scale. *Appl. Psychol.* 1, 37–40. doi: 10.3969/j.issn.1006-6020.2001.01.007

Wang, J. S., Li, Y., and He, E. S. (1997). Compilation and standardization of the mental health scale for Chinese middle school students. *Soc. Psychol. Sci.* 4:6.

Wang, X., Liu, T., Jin, X., and Zhou, C. (2024). Aerobic exercise promotes emotion regulation: a narrative review. *Exp. Brain Res.* 242, 783–796. doi: 10.1007/s00221-024-06791-1

World Health Organization. (2020). APA 7th edition: adolescents health. Available at: https://www.who.int/health-topics/adolescent-health/#tab=tab_1.

Wu, Z., Wang, B., Xiang, Z., Zou, Z., Liu, Z., Long, Y., et al. (2022). Increasing trends in mental health problems among urban Chinese adolescents: results from repeated cross-sectional data in Changsha 2016–2020[J]. *Front. Public Health* 10:829674. doi: 10.3389/fpubh.2022.829674

Xie, W., Ye, C., and Zhang, W. (2023). Negative emotion reduces visual working memory recall variability: a meta-analytical review. *Emotion* 23, 859–871. doi: 10.1037/emo0001139

Yan, Z., Qiu, S., Alizadeh, A., and Liu, T. (2021). How challenge stress affects mental health among college students during the COVID-19 pandemic: The moderating role of self-efficacy. *Int. J. Ment. Health Promot.* 23, 167–175. doi: 10.32604/IJMHP.2021.015937

Yu, H., Lee, L., Popa, I., and Madera, J. M. (2021). Should I leave this industry? The role of stress and negative emotions in response to an industry negative work event. *Int. J. Hosp. Manag.* 94:102843. doi: 10.1016/j.ijhm.2020.102843

Yu, H., Zhu, T., Tian, J., Zhang, G., Wang, P., Chen, J., et al. (2024). Physical activity and self-efficacy in college students: the mediating role of grit and the moderating role of gender. *PeerJ* 12:e17422. doi: 10.7717/peerj.17422

Zhang, G., Feng, W., Zhao, L., Zhao, X., and Li, T. (2024). The association between physical activity, self-efficacy, stress self-management and mental health among adolescents. *Sci. Rep.* 14:5488. doi: 10.1038/s41598-024-56149-4

Zhang, Q., Zhou, L., and Xia, J. (2020). Impact of COVID-19 on emotional resilience and learning management of middle school students. *Med. Sci. Monit.* 26, e924994–e924991. doi: 10.12659/MSM.924994

Zhao, Z., Sarkhani, S., Sarkhani, M., and Imani, N. (2023). Effect of a home-based exercise programme on mental health and well-being in children during COVID-19 pandemic. *Int. J. Sport Exerc. Psychol.* 21, 1006–1023. doi: 10.1080/1612197X.2022.2109186

Zou, L., Wang, T., Herold, F., Ludyga, S., Liu, W., Zhang, Y., et al. (2023). Associations between sedentary behavior and negative emotions in adolescents during home confinement: mediating role of social support and sleep quality. *Int. J. Clin. Health Psychol.* 23:100337. doi: 10.1016/j.ijchp.2022.100337

Zullig, K. J., and White, R. J. (2011). Physical activity, life satisfaction, and self-rated health of middle school students. *Appl. Res. Qual. Life* 6, 277–289. doi: 10.1007/s11482-010-9129-z

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 12 November 2024
DOI 10.3389/fpsyg.2024.1436611

Check for updates

OPEN ACCESS

EDITED BY
Jose Mora-Gonzalez,
University of Granada, Spain

REVIEWED BY
Stefania Mancone,
University of Cassino, Italy
Mark T. Elliott,
University of Birmingham, United Kingdom
Ermilo Canton-Martinez,
Universidad Autónoma de Baja California,
Ensenada, Mexico

*CORRESPONDENCE
Rodrigo Antunes Lima
✉ rodrigoantunes.lima@sjd.es

†These authors share last authorship

RECEIVED 22 May 2024
ACCEPTED 07 October 2024
PUBLISHED 12 November 2024

CITATION
Ibáñez D, Condominas E, Haro JM, Vázquez IG, RADAR-MDD-Spain, Bailón R, Garcia E, Kontaxis S, Peñarrubia-Maria MT, Arranz B, Llaosa-Scholten R, Gardeñes L, Hotopf M, Matcham F, Lamers F, Penninx BWJH, Annas P, Folarin A, Narayan V, Lima RA, Siddi S and the RADAR CNS consortium (2024) Pre- and post-COVID 19 outbreak relationship between physical activity and depressive symptoms in Spanish adults with major depressive disorder: a secondary analysis of the RADAR-MDD cohort study. *Front. Psychol.* 15:1436611. doi: 10.3389/fpsyg.2024.1436611

Pre- and post-COVID 19 outbreak relationship between physical activity and depressive symptoms in Spanish adults with major depressive disorder: a secondary analysis of the RADAR-MDD cohort study

Delia Ibáñez[1,2], Elena Condominas[3,4], Josep Maria Haro[3,5], Iago Giné Vázquez[3,5], RADAR-MDD-Spain, Raquel Bailón[5,6], Esther Garcia[7,8], Spyridon Kontaxis[3,6], Maria Teresa Peñarrubia-Maria[9,10,11], Belen Arranz[3,5], Raúl Llaosa-Scholten[12], Lluisa Gardeñes[9], Matthew Hotopf[13,14], Faith Matcham[13,15], Femke Lamers[16,17], Brenda W. J. H. Penninx[16,17], Peter Annas[18], Amos Folarin[13], Vaibhav Narayan[19], Rodrigo Antunes Lima[3,5*†], Sara Siddi[3,5†] and the RADAR CNS consortium

[1]Department of Psychiatry and Psychology, Hospital Clinic of Barcelona, Barcelona, Spain, [2]Faculty of Medicine, Universitat Autònoma de Barcelona, Barcelona, Spain, [3]Centro de Investigación Biomédica en Red de Salud Mental (CIBERSAM), Instituto de Salud Carlos III, Madrid, Spain, [4]Universitat Politécnica de Catalunya, Barcelona, Spain, [5]Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain, [6]Aragón Institute of Engineering Research (I3A), Instituto de Investigación Sanitaria de Aragón (IIS Aragón), University of Zaragoza, Zaragoza, Spain, [7]Centros de Investigación Biomédica en Red en el Área de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Madrid, Spain, [8]Microelectrónica y Sistemas Electrónicos, Universidad Autónoma de Barcelona, Bellaterra, Spain, [9]Consortium for Biomedical Research in Epidemiology and Public Health (CIBERESP), Instituto de Salud Carlos III, Madrid, Spain, [10]Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain, [11]Consorcio de Investigación Biomédica en Red de Epidemiología y Salud Pública (CIBERESP), Instituto de Salud Carlos III, Madrid, Spain, [12]FEA Psicología Clínica, HU Institut Pere Mata, Vendrell, Spain, [13]Institute of Psychiatry, Psychology and Neuroscience, King's College London, London, United Kingdom, [14]South London and Maudsley NHS Foundation Trust, London, United Kingdom, [15]School of Psychology, University of Sussex, East Sussex, United Kingdom, [16]Department of Psychiatry, Amsterdam UMC Location Vrije Universiteit Amsterdam, Amsterdam, Netherlands, [17]Amsterdam Public Health, Mental Health Program, Amsterdam, Netherlands, [18]H. Lundbeck A/S, Valby, Denmark, [19]Department of Psychiatry, University of Oxford, Warneford Hospital, Oxford, United Kingdom

Aim: To evaluate the longitudinal association of sedentary behavior, light and moderate-to-vigorous physical activity (MVPA) participation with depressive symptoms and whether their possible association changed depending on the pandemic phase.

Methods: This longitudinal study conducted secondary analysis from the Spanish cohort of the Remote Assessment of Disease and Relapse – Major Depressive Disorder (RADAR-MDD) study. Depressive symptoms were assessed by the Patient Health Questionnaire (PHQ-8). Sedentary behavior and physical activity were estimated via wrist-worn devices. Linear mixed models evaluated the longitudinal associations of sedentary behavior and physical activity (light and moderate-to-vigorous intensities) with depressive symptoms.

Results: In total, 95 participants (67.5% women, 53.0 [±10.5] years of age on average) were monitored pre-COVID-19 and included in the analyses. Pre-COVID-19, 73.7% of participants presented depression, and, on average, participated in 13.2 (±1.08) hours/day of sedentary behavior, 2.42 (±0.90) hours/day of light physical activity and 23.6 (±19.80) minutes/day of MVPA. Considering all the observations (from November 2019 to October 2020), an additional hour/day of sedentary behavior was longitudinally associated with higher depressive symptoms [βstd=0.06, 95% confidence interval (CI) 0.10 to 0.47], whereas an additional hour/day in light physical activity was associated with lower depressive symptoms (βstd=−0.06, 95% CI −0.59 to −0.15). Time in MVPA was not associated with depressive symptomatology. The association of sedentary behavior and light physical activity with depressive symptoms was significant only during pre-COVID-19 and COVID-19 relaxation periods, whereas during the strictest periods of the pandemic with regards to the restrictions (lockdown and de-escalation), the association was not observed.

Conclusion: Sedentary behavior and light physical activity were longitudinally associated with depressive symptoms in participants with a history of MDD. The incorporation of light physical activity should be stimulated in adults with a history of MDD. Neither sedentary behavior nor light physical activity were associated with depressive symptoms during the most restrictive COVID-19 phases, whereas sedentary behavior (positively) and light physical activity (negatively) were associated with depressive symptoms in persons with MDD before and after the COVID-19 pandemic.

KEYWORDS

COVID-19, major depressive disorder, depression, depressive symptoms, physical activity

1 Introduction

Depressive disorders are the second leading cause of years lived with disability (GBD 2019 Mental Disorders Collaborators, 2022). A severe form of depression is Major Depressive Disorder (MDD). An MDD episode is diagnosed when low mood and anhedonia occur combined with a range of other symptoms, such as changes in sleep quality, appetite, cognitive function, physical inactivity, asthenia, suicide ideation, and feelings of guilt or worthlessness (American Psychiatric Association, 2013; Beratis et al., 2005; Wagner et al., 2020). MDD has a worldwide prevalence of 2470.5 cases per 100,000 individuals; since the COVID-19 pandemic, its prevalence has increased by 27.6% (COVID-19 Mental Disorders Collaborators, 2021). Approximately, 55% of adults who suffer from MDD will develop chronic depression, characterized by periods of recovery and relapse (Hardeveld et al., 2013; Verduijn et al., 2017).

More recently, growing evidence indicates that physical activity can be a valuable protective factor against depression and a treatment that can mitigate depressive symptoms in persons with MDD (Dishman et al., 2021; Hanssen et al., 2018; Minghetti et al., 2018; Nasstasia et al., 2019; Schuch and Stubbs, 2019; Stubbs et al., 2018), whereas time in sedentary behavior has been associated with a higher risk of developing MDD (Hallgren et al., 2018). Nevertheless, a series of limitations restrict the strength and extension of the evidence.

The number of longitudinal studies, especially with multiple monitoring periods, is scarce (Gianfredi et al., 2021; Hallgren et al., 2018, 2020; Keating et al., 2018). Furthermore, the majority of the current evidence is based on questionnaire-based (indirect) assessment of physical activity and sedentary behavior when evaluating their relationship with depression in persons with MDD (Brondino et al., 2017; de Souza Moura et al., 2015; Krogh et al., 2017; Schuch et al., 2016a; Schuch et al., 2016b). The use of direct assessment, such as accelerometer for the estimation of physical activity level and sedentary behavior, result in more precise and detailed information. Particularly, accelerometers measure the time dedicated to different physical activity intensities (e.g., light and moderate-to-vigorous) during a particular week besides not relying on the memory of the person, avoiding recall bias. Finally, it is also unclear whether the COVID-19 pandemic affected the relationships of sedentary behavior and physical activity with depression in adults with a history of MDD.

Therefore, we evaluated the longitudinal association of sedentary behavior and physical activity with depression in patients with a history of recurrent MDD from the Spanish sample of the Remote Assessment of Disease and Relapse - Major Depressive Disorder (RADAR-MDD) cohort study (Matcham et al., 2019, 2022). Moreover, we evaluated whether the longitudinal association of sedentary behavior and physical activity with depression changed depending on

Abbreviations: MDD, Major depressive disorder; MVPA, Moderate-to-vigorous physical activity; RADAR-MDD, Remote Assessment of Disease and Relapse – Major Depressive Disorder; RADAR-CNS, Remote Assessment of Disease and Relapse – Central Nervous System; LIDAS, Lifetime Depression Assessment – Self-Report; PHQ-8, The Patient Health Questionnaire-8; MVPA, Moderate to Vigorous Physical Activity; ML, maximum likelihood; SB, sedentary behavior; PA, physical activity.

the period of the pandemic (pre-COVID-19, COVID-19 lockdown, de-escalation and relaxation).

The RADAR-MDD study provides a unique opportunity to address the aforementioned objectives (Leightley et al., 2021; Siddi et al., 2022; Sun et al., 2020). First, RADAR-MDD followed participants with MDD since before the COVID-19 outbreak including different phases of the pandemic with multiple monitoring periods (lockdown, de-escalation and relaxation). Second, the study contains direct assessment of physical activity and sedentary behavior, which means higher data quality compared to most of the previous investigations (Currier et al., 2020; Hallgren et al., 2018, 2020; Kaseva et al., 2019; Nasstasia et al., 2019; Stevens et al., 2021). Third, RADAR-MDD monitored participants with MDD in Spain which imposed more restrictive measures than other countries related to outdoors activities and more stringent COVID-19 policies have been associated with poorer mental health (Aknin et al., 2022; Hale et al., 2021; Lavalle et al., 2023). These measures were quantified using the stringency index, with Spain, the Netherlands, and the UK registering indices of 85.2, 78.7, and 79.6, respectively, from February to the first of October 2020, as measured by the COVID-19 government response tracker (Mathieu et al., 2020). Therefore, it is possible to evaluate the effects of this level of restrictions on the relationship of sedentary behavior, physical activity with depression.

2 Materials and methods

2.1 Study design

This is a secondary analysis from the Spanish cohort of the longitudinal RADAR-MDD research project. In summary, RADAR-MDD study is a collaborative research project carried out in Netherlands, United Kingdom, and Spain (Ranjan et al., 2019). This project is part of the Remote Assessment of Disease and Relapse – Central Nervous System (RADAR-CNS) consortium,[1] aimed at providing real-time multidimensional indicators of symptoms changes and relapse of individuals with three different health conditions: MDD, multiple sclerosis and epilepsy in order to improve treatment and prevention (Matcham et al., 2019).

The RADAR-MDD dataset allows for detailed monitoring of behavioral and depressive symptoms changes in a sample with a history of MDD (Matcham et al., 2022; Ranjan et al., 2019). RADAR-CNS developed the open-source RADAR-Base platform for data collection and storage from wearables and mobile technologies[2] (Ranjan et al., 2019). Radar-base provides both passive and active data collection using active and passive remote measurement technology (Ranjan et al., 2019).

The project was co-designed and conducted in partnership with service users in the Patient Advisory Board of the RADAR-CNS study (Matcham et al., 2022; Simblett et al., 2020). They were involved in the choice of measures, the timing and issues of engagement (Simblett et al., 2019, 2020). The full protocol for RADAR-MDD has been reported previously (Matcham et al., 2022).

2.2 Study population

The current study included participants from the RADAR-MDD study in Spain who were monitored between November 2017 and October 2020 when the COVID-19 wave started (Real Decreto 926/2020, de 25 de octubre, n°286, 2020). Adults diagnosed of recurrent MDD during their life, who were living in Spain were enrolled from a clinical sample of individuals seeking help for a mental health condition (Matcham et al., 2019).

To be eligible for participation in RADAR-MDD, individuals must: (1) have met DSM-5 (Diagnostic and Statistical Manual of Mental Disorders, 5th edition) diagnostic criteria for non-psychotic MDD within the past 2 years; (2) have recurrent MDD (a lifetime history of at least 2 episodes of depression); (3) be willing and be able to complete self-reported assessments via smartphone; (4) be able to give informed consent for participation; (5) Fluent in Spanish or Catalan; (6) existing ownership of Android smartphone or willingness to use an Android smartphone as their only smartphone; (7) aged 18 or older (Matcham et al., 2022).

The exclusion criteria included: (1) have a lifetime history of bipolar disorder, schizophrenia, MDD with psychotic features, or schizoaffective disorders; (2) dementia; (3) history of moderate to severe drug or alcohol dependence within the last 6 months prior to enrolment; (4) history of major medical disease which might impact upon the patient's ability to participate in normal daily activities for more than 2 weeks (e.g., due to likely hospitalizations or other periods of indisposition); (5) Pregnancy (although once enrolled, becoming pregnant did not result in withdrawal) (Matcham et al., 2022).

No limitations have been applied regarding any treatment they may be receiving, although medication use and other psychological interventions were monitored throughout the course of follow-up. Additionally, participants were eligible to participate regardless of whether they were currently experiencing depression symptoms or not (Matcham et al., 2022).

In Spain, eligible participants were identified through primary and secondary mental health services or through advertisements for the study placed on mental health charity websites, circulars or Twitter notices (Matcham et al., 2022). Informed consent from all potential participants who fulfilled inclusion and exclusion criteria was obtained. The research was conducted in accordance with the Helsinki Declaration of 1975, as revised in 2008.

In total, 155 Spanish participants met the eligibility criteria and were eligible to participate in the RADAR-MDD study (Matcham et al., 2019). All participants provided written consent previous to the enrolment session (Matcham et al., 2019). For enrolment, depression diagnosis was assessed using the Lifetime Depression Assessment – Self-Report (LIDAS) in addition to the review of medical records (Bot et al., 2017; Matcham et al., 2022).

For the current study, the monitoring period was subdivided into four categories as follows (Lavalle et al., 2023; Cataluña. Departament d' Interior, 2020; Cataluña. Departament de Salut, 2020; España. Jefatura del Estado, 2020; España. Ministerio de la Presidencia, Relaciones con las Cortes y Memoria Democrática, 2020; España. Ministerio de Sanidad, 2020a,b,c):

- Pre-COVID-19 phase: immediately before the first restrictive measure in relation to the COVID-19 pandemic; November 1st, 2019 to March 10th, 2020 (total of 130 days).

1 https://www.kcl.ac.uk/research/radarcns
2 http://radar-base.org/

- COVID-19 lockdown refers to the period of the national lockdown in Spain from March 11th, 2020 to April 26th, 2020 (total of 46 days). Specifically, on March 11th, 2020, the Government of Catalonia introduced social distancing to fight the spread of COVID-19 (Resolució SLT/704/2020, d'11 de març, n° 8082A, 2020). On March 14, 2020, the Spanish Government established strict lockdown measures after the declaration of the State of Alarm (Real Decreto 463/2020, de 14 de marzo, BOE nª 3,692, 2020).
- COVID-19 de-escalation refers to the period between April 27th, 2020 and June 18th, 2020 (total of 52 days) when restrictions were lifted gradually through four phases implemented by the Spanish government and supplementary measures of the local Catalan government. See the phases below:
  - o During phase 0 non-essential businesses were opened by appointment, and citizens were allowed to do outdoor physical activity by time slot based on age (Orden SND/386/2020, de 3 de mayo, BOE n° 123, 2020).
  - o Phase 1 meetings with a maximum of 10 people were allowed; only outdoor spaces of bars and restaurants opened, as well as some spaces of culture, museums, and gyms; transfers to a second residence were permitted (Orden SND/399/2020, de 9 de mayo, n° 130, 2020).
  - o Phases 2 and 3 time slots were finished and bars and restaurants' openings were extended even to the indoor areas, with limited capacity; shopping centers opened, public transport restarted working at 100% and the percentage of capacity in cinemas, theatres, museums increased (Orden SND/414/2020, de 16 de mayo, n° 136, 2020).
- COVID-19 relaxation phase: period between June 19th, 2020 and October 16th, 2020 (total of 119 days) when the mots of the restrictions related to COVID-19 pandemic were eased (Resolució INT/1433/2020, 18 de junio, n° 8,160, 2020; Real Decreto 926/2020, de 25 de octubre, n° 286, 2020).

2.3 Assessments

2.3.1 Depressive symptoms

Depressive symptoms were assessed using The Patient Health Questionnaire (PHQ-8) every 2 weeks via the project app (active remote measurement technology) (Matcham et al., 2019). The PHQ-8 is an 8-item self-report questionnaire which measures the frequency of depressive symptoms over the preceding 2-week period (Gómez-Gómez et al., 2023; Kroenke et al., 2009). Each item is rated from 0 = "not at all" to 3 = "nearly every day," producing a range of total scores from 0 to 24 (increasing severity), which was used for the main analyses (Gómez-Gómez et al., 2023; Kroenke et al., 2009).

For descriptive purposes, participants with a score of ≥10 were classified with depression since it is the most recommended cut-off point for "clinically relevant" depressive symptoms in the previous two weeks (Kroenke et al., 2009).

2.3.2 Physical activity and sedentary behavior

Physical activity and sedentary behavior were estimated through Fitbit devices (Fitbit Charge 2 and 3; Fitbit Inc., San Francisco, CA, USA), which were given to participants (Leightley et al., 2021). Participants were asked to wear the Fitbit devices on the wrist of the non-dominant hand for the duration of the monitoring period. Fitbit 2 or 3 wristband devices are a 3-axis accelerometer-based activity trackers (Matcham et al., 2019). This accelerometer model was chosen by the RADAR-CNS project members together with the volunteers for being commercially available, minimally invasive and easy to use (Polhemus et al., 2020; Simblett et al., 2020).

Fitbit uses a proprietary algorithm which converts raw acceleration data into activity counts in 60-s sampling intervals that define activity intensities classifying each minute as being in sedentary, light, moderate, or vigorous activity (Fitbit Inc, 2018; Hartman et al., 2018; Mikkelsen et al., 2020). We used the daily time spent in sedentary, light and moderate-to-vigorous physical activity (MVPA; moderate + vigorous time) intensities. We only included participants with at least 3 days of physical activity registration and a minimum of 8 valid hours per day in each of the monitoring periods (pre-COVID-19, COVID-19 lockdown, COVID-19 de-escalation and COVID-19 relaxation). For each intensity, we calculated the average time per day dedicated to sedentary behaviour and physical activity considering a day with 16 h (24 h – 8 h of sleep).

Among the 155 participants in the study, 95 fulfilled the required monitoring parameters in the pre-Covid phase, 47 during the lockdown, 46 in the de-escalation phase, and 50 in the COVID-19 relaxation phase.

2.3.3 Confounders

Sociodemographic data (age, sex, marital status [with a partner, single, separated/divorced and widowed]) and comorbidity with other medical illness were collected through a questionnaire at baseline.

2.3.4 Assessments completed by participants per study period

Participants were often monitored (i.e., asked to complete questionnaires and had their physical activity tracked via Fitbit, etc.) multiple times during each of the COVID-19 phases (Pre-COVID-19, COVID-19 lockdown, COVID-19 de-escalation, and COVID-19 relaxation). Table 1 presents the average number of times participants were asked to perform assessments in each COVID-19 phase. For analyses, we included the average of all assessments per participant within each COVID-19 phase, providing a comprehensive representation of their monitoring data during that period.

2.4 Data analysis

Descriptive analyses used frequencies and unweighted percentages for categorical variables, and means and standard deviations for continuous variables.

Linear mixed-model with random effects of participants and estimated with maximum likelihood (ML) method, using library nlme

TABLE 1 Average Monitoring Periods per Subject in Each COVID-19 Phase.

COVID-19 phase	Mean (std)	Persons
Pre-COVID-19	10.92 (8.06)	95
COVID-19 lockdown	2.26 (1.01)	47
COVID-19 de-escalation	2.54 (1.00)	46
COVID-19 relaxation	4.62 (2.62)	50

in R were conducted to evaluate the association of sedentary behavior and each physical activity intensity (light and MVPA) with depressive symptoms severity (Pinheiro and Bates, 2000; R Core Team, 2023). We considered the pandemic restrictions and the lockdown as a categorical variable in the model (hereafter COVID-19 phases).

We analyzed the longitudinal relationship of sedentary behavior, physical activity (light physical activity, and MVPA) with depressive symptoms (PHQ-8 scores); results presented in the Table 2 and in section 3.1. All analysis presented in Table 2 included all 1,491 observations from 95 participants who were monitored longitudinally between November 1st, 2019 and October 16th, 2020. As described previously, each participant could have been monitored in multiple opportunities in each COVID-19 phase, but only one observation per phase for each participant was included in the model. In the model 1 of the Table 2, each of the exposures (sedentary behavior, light physical activity, and MVPA) were evaluated in separate models in relation to depressive symptoms. In the model 2 of the Table 2, sedentary behavior and light PA models were adjusted by MVPA, whereas the MVPA model was adjusted by sedentary behavior. Analysis in the models 1 and 2 in the Table 2 were also adjusted by sex, age, comorbidity and monitoring phase. There were no significant differences in sociodemographic variables between participants across different COVID-19 phases.

In addition, we ran an linear mixed-model with random effects of participants and adjusted by ML method to evaluate whether the association of sedentary behavior and physical activity intensities (light and MVPA) with depressive symptoms differed depending on the COVID-19 phase; analyses described in the subsection 3.2. Figure 1 presents the association of sedentary behavior and MVPA with depressive symptoms across different COVID-19 phases whereas Figure 2 for light physical activity and MVPA with depressive symptoms across different COVID-19 phases. Both models included an interaction term between the exposures and the COVID-19 phase to estimate the strength of the association within each COVID-19 phase while accounting for the longitudinal structure of the data. All linear mixed-model analyses were adjusted by age, sex and comorbidity of other medical illness (Akhtar-Danesh and Landeen, 2007; Aluoja et al., 2004; Gutiérrez-Rojas et al., 2020). In the first step, we attempted to adjust for education level and marital status, but these variables did not contribute significantly to the model. We applied an ANOVA analysis to confirm that there were no significant differences when these variables were included or excluded.

In all multivariable models, we accepted a type I error of 5%.

3 Results

In total, 95 adults were included in the present study with; mean age of 53.0 (±10.2) years, 69.5% were female, 60.0% were cohabiting or married and 57.9% had comorbidities at baseline. The majority (73.7%) exhibited depression before the COVID-19 pandemic and were regular on antidepressant medications, with a mean PHQ-8 score of 13.7 (±5.98) points (Table 3). The number of participants monitored was 47 in the COVID-19 lockdown, 46 in the COVID-19 de-escalation and 50 in the COVID-19 relaxation phase. We did not observe attrition bias at follow up compared to baseline characteristics.

Table 4 presents the average of depression score, time in sedentary behavior and in distinct physical activity intensities in each of the monitoring periods.

3.1 Longitudinal association of sedentary behavior and physical activity (light and MVPA) with depressive symptoms in participants with MDD in Spain

An additional hour/day of sedentary behavior was longitudinally associated with higher depressive symptoms ($\beta = 0.29$ score of PHQ-8, 95% CI 0.10 to 0.47; Table 2, model 1), whereas an additional hour/day in light physical activity was associated with lower depressive symptoms ($\beta = -0.37$ score of PHQ-8, 95% CI −0.59 to −0.15; Table 2, model 1). Time in MVPA was not associated with depressive symptoms. Both sedentary behavior and light physical activity continued to be associated with depressive severity independent of time spent in MVPA (Table 2, model 2). Supplementary Table S1 presents the coefficients from Model 1 of Table 2, including the coefficients for the confounders that adjusted the models.

3.2 Longitudinal association of sedentary behavior and physical activity (light and MVPA) with depressive symptoms across monitoring phases

The association of sedentary behavior and light physical activity with depressive symptoms varied depending on the monitoring period, whereas MVPA was not associated with depressive symptoms in any of the monitoring phases. Particularly, both sedentary behavior (Figure 1) and light physical activity (Figure 2) were associated with depressive symptoms at the pre-COVID-19 phase and during the COVID-19 relaxation periods. Sedentary behavior was associated with increased depression in the pre-COVID-19 phase ($\beta = 0.37$, CI 0.12–0.62) and during the COVID-19 relaxation phase ($\beta = 0.47$ CI 0.14–0.81). On the other hand, light physical activity was associated with decreased depression in the pre-COVID-19 phase ($\beta = -0.38$, CI −0.64 – −0.13) and during the COVID-19 relaxation phase ($\beta = -0.45$, CI −0.81 – −0.08) (Table 5).

4 Discussion

In this study, we investigated the longitudinal association of sedentary behavior as well as different physical activity intensities with depressive symptoms in a cohort of Spanish adults with a recent history of MDD across COVID-19 phases. Sedentary behavior, positively, and light physical activity, negatively, were associated with depressive symptoms in participants with a history of MDD, whereas time in MVPA was not (results presented in Table 2). Furthermore, we observed that an additional hour/day of sedentary behavior is related to higher depressive severity during the pre-COVID-19 and the relaxation phases (results presented in Figure 1). Besides, an extra hour/day of light physical activity is associated with lower depressive symptomatology during the same phases (results presented in Figure 2), whereas MVPA was not associated with depressive symptoms in any COVID-19 phases.

Although sedentary behavior and light physical activity were determinants of depressive symptoms, their importance in relation to depressive symptomatology in adults with MDD was weakened during the strictest periods of the COVID-19 pandemic. Of note, both

TABLE 2 Longitudinal associations of sedentary behavior, light physical activity (light PA) and moderate-to-vigorous PA (MVPA) with depressive symptoms (PHQ-8 score) in participants with MDD in Spain.

Model 1					Model 2				
PHQ-8	ß (score of PHQ-8)	βstd	(95% CI)	*p*-value	PHQ-8	ß (score of PHQ-8)	βstd	(95% CI)	*p*-value
Sedentary behavior	0.29	0.055	(0.10 to 0.47)	0.002	Sedentary behavior	0.37	0.071	(0.15 to 0.60)	0.001
Light PA	−0.37	−0.059	(−0.59 to −0.15)	0.001	Light PA	−0.35	−0.059	(−0.57 to −0.12)	0.003
MVPA	−0.003	−0.013	(−0.01 to 0.005)	0.430	MVPA	0.01	0.026	(−0.004 to 0.017)	0.211

PA refers to physical activity; Model 1: each of the exposures were evaluated in separate models; Model 2: Sedentary behavior and Light PA models were further adjusted by MVPA, whereas the MVPA model was adjusted by sedentary behavior. Models 1 and 2 were adjusted by sex, age, comorbidity and monitoring phase; CI refers to confidence interval.

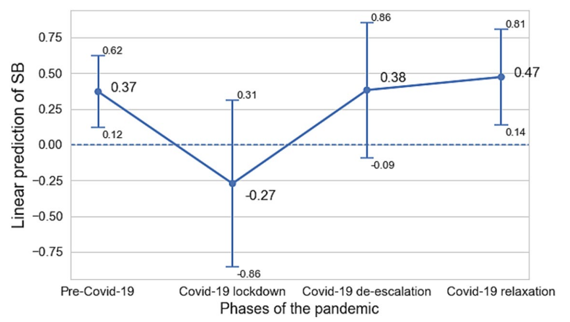


FIGURE 1
Longitudinal association between sedentary behavior and depressive severity across COVID-19 phases. Values are represented as average marginal effects and 95% confidence intervals.

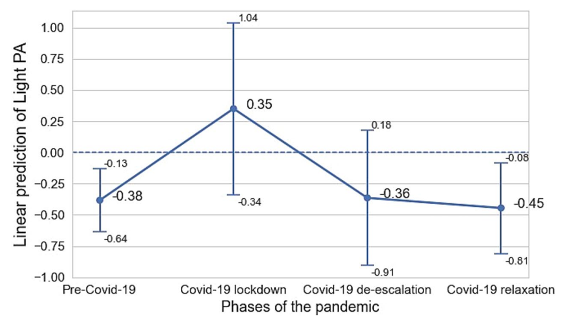


FIGURE 2
Longitudinal association between light PA and depressive severity across COVID-19 phases. Values are represented as average marginal effects and 95% confidence intervals.

TABLE 3 Sociodemographic characteristics at baseline.

Characteristic	Pre-COVID-19 (*n* = 95)
Age, in years Mean (SD)	53.0 (±10.2)
Sex *n* (%)	
Female	66 (69.5%)
Male	29 (30.5%)
Marital status *n* (%)	
With a partner	57 (60.0%)
Without a partner (Single/Separated, Divorced/Widowed)	38 (40.0%)
Comorbidity with other medical illness *n* (%)	
Yes	55 (57.9%)
No	40 (42.1%)
Depression *n* (%)	
Yes	70 (73.7%)
No	25 (26.3%)

SD refers to standard deviation, Depression as measured by PHQ-8.

sedentary behavior and light physical activity returned to be associated with depressive symptoms after easing the COVID-19 restrictions. It is possible that other factors related to the pandemic (worry of being infected, social isolation, unemployment, economic losses, changes in daily routines and social dynamics) were more relevant to their mental health during the most restrictive phases of the pandemic. It is also possible that the restrictions due to the COVID-19 pandemic restricted people from performing physical activities.

Our findings suggest that light physical activity might be more relevant than MVPA in relation to the depressive symptomatology of adults with a history of MDD. Of note, a recent systematic review and network meta-analysis of randomized controlled trials concluded that exercises prescribed in higher intensities showed higher reduction in depressive symptomatology in adults with clinical cut-offs for major depression (Noetel et al., 2024). To date, the state-of-the-art did not reach a consensus on the varying impact of different intensities of physical activity on depressive symptoms.

Experimental studies demonstrate that exercise, whether of lower or higher intensity, positively affects depressive symptoms in adults with depression (Hanssen et al., 2018; Noetel et al., 2024) and those with major depressive disorder (MDD) (Minghetti et al., 2018; Nasstasia et al., 2019; Schuch and Stubbs, 2019; Stubbs et al., 2018). Some studies suggest a more significant impact on depressive symptoms with higher exercise intensities (Hanssen et al., 2018; Noetel et al., 2024). It is speculated that higher intensities may lead to greater reductions in depressive symptoms due to enhanced physiological responses, such as reduced inflammation, oxidative stress, and increased neuronal regeneration (Schuch and Stubbs, 2019; Stubbs et al., 2018; Kandola et al., 2019).

Observational studies using questionnaires to assess physical activity levels report stronger associations between moderate-to-vigorous physical activity (MVPA) and reduced depressive symptoms compared to light physical activity (LPA) (Dishman et al., 2021; Wolf et al., 2021; Schuch et al., 2018). However, a recent study using accelerometry found that LPA was more protective against incident depression than higher

TABLE 4 Depressive symptoms (PHQ-8 score), and time spent in sedentary behavior and in different physical activity intensities across COVID-19 phases.

	Pre-COVID-19	COVID-19 lockdown	COVID-19 de-escalation	COVID-19 relaxation
Depressive symptoms, PHQ-8 score	13.7 (5.98)	14.0 (6.80)	13.9 (6.71)	12.6 (6.78)
Sedentary behavior, hours/day	13.2 (1.08)	14.0 (0.95)	13.7 (1.17)	13.3 (1.19)
Light PA, hours/day	2.42 (0.90)	1.77 (0.80)	1.92 (1.02)	2.32 (1.07)
Moderate PA, min/day	13.3 (13.0)	8.27 (12.5)	9.56 (11.9)	11.8 (11.5)
Vigorous PA, min/day	10.3 (9.69)	5.44 (8.81)	10.7 (14.3)	10.7 (11.0)
Moderate-to-vigorous PA, min/day	23.6 (19.8)	13.7 (19.0)	20.3 (23.1)	22.5 (18.8)

Data presented as means and (standard deviations). PHQ-8 score ranges between 0 and 24 points. PA refers to physical activity.

TABLE 5 The STROBE checklist of the study.

	Item No.	Recommendation	Page No.
Title and abstract	1	(a) Indicate the study's design with a commonly used term in the title or the abstract	1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3
Objectives	3	State specific objectives, including any prespecified hypotheses	3–4
Methods			
Study design	4	Present key elements of study design early in the paper	4
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	4–6
Participants	6	(a) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case–control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	4–6
		(b) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case–control study*—For matched studies, give matching criteria and the number of controls per case	
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6
Data sources/ measurement	8	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	6
Bias	9	Describe any efforts to address potential sources of bias	6–7
Study size	10	Explain how the study size was arrived at	5–6

intensities (Lima et al., 2024). This divergence may be attributed to the methods of physical activity assessment. Previous research has shown conflicting health associations depending on whether physical activity was assessed via questionnaires or accelerometers (Gill et al., 2023).

Questionnaires, relying on self-reported data, are prone to recall bias and social desirability bias, which can lead to inaccurate estimations of activity levels. Adults with lower physical activity levels might perceive and report low-intensity activities as higher intensity due to their lower fitness levels and subjective experiences, further distorting the data. In contrast, accelerometers provide objective, continuous data, reducing reporting bias and offering a more accurate measure of overall physical activity. However, they often fail to capture specific activity types, such as swimming or cycling, and may miss context-specific nuances of physical activity patterns. These discrepancies in data capture methods can significantly influence the observed associations between physical activity and health outcomes in studies (Gill et al., 2023).

Psychosocial mechanisms might explain the association between LPA and depressive symptoms in adults with MDD (Kandola et al., 2019; Schuch et al., 2018). In particular, a person with MDD might be more likely to perform a physical activity in the company of a partner, a friend or a family member in lower physical activity intensity, strengthening their social support and self-esteem, which might decrease their depressive symptomatology (Kandola et al., 2019; Schuch et al., 2018). Noteworthy, the lack of association between MVPA and depressive symptoms in the current study might be due to the limited number of minutes in MVPA, which could have been too discreet to provide mental health benefits. Nevertheless, participation in MVPA should also be encouraged because of the numerous health benefits and our results do not suggest that participation in MVPA is deleterious to the mental health of patients with MDD (Hallgren et al., 2016; Schuch et al., 2018; Sheikh et al., 2018).

Notwithstanding the strengths of our study, it does have some limitations. First, participant adherence to the study protocol (i.e., questionnaire completion or wearing de wristband device) decreases during the most restrictive periods which contributed to the limited number of participants included in the analyses ($n = 95$). Nevertheless, our analysis included all the information available on each participant who contributed with data in at least one monitoring period. Importantly, the use of direct assessment of physical activity during different monitoring periods, including the pandemic, overcome a pivotal limitation of previous studies.

Second, participants recruited at different times may use different devices for smartphones and Fitbit depending on the availability and enrolment dates, which might have impacted on the estimation of physical activity and sedentary behavior. Nevertheless, recent meta-analyses observed that Fitbit model is not a significant factor impacting on the device validity (Leung et al., 2022).

Third, while our longitudinal study provides valuable insights into the relationship between physical activity levels and depressive symptoms among adults with major depressive disorders, the potential for reverse causality, selection bias and observation bias should be acknowledged as they may influence the generalizability and accuracy of our findings.

5 Conclusion

Sedentary behavior, positively, and light physical activity, negatively, were associated with depressive symptoms in participants with a history of MDD, whereas time in MVPA was not. The incorporation of light physical activity should be stimulated by mental health professionals, future public health programs and research interventions aiming to decrease depressive symptomatology in adults with a history of MDD, especially by diminishing time in sedentary activities.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Camberwell St Giles Research Ethics Committee (REC reference: 17/LO/1154), in London, from the CEIC Fundació Sant Joan de Deu (CI: PIC-128-17), in Barcelona, and from the Medische Ethische Toetsingscommissie Vums (METcVumc registratienummer: 2018.012–NL63557.029.17), in the Netherlands. RADAR-CNS was conducted per the Declaration of Helsinki and Good Clinical Practice, adhering to principles outlined in the NHS Research Governance Framework for Health and Social Care (2nd edition). The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

RADAR CNS consortium

https://www.kcl.ac.uk/research/radarcns

Author contributions

DI: Conceptualization, Writing – original draft, Writing – review & editing. EC: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. JH: Conceptualization, Investigation, Validation, Writing – review & editing, Project administration, Resources, Supervision. IV: Writing – review & editing, Software. RADAR-MDD-Spain: Writing – review & editing. RB: Writing – review & editing. EG: Writing – review & editing. SK: Writing – review & editing. MP-M: Writing – review & editing. BA: Writing – review & editing. RL-S: Writing – review & editing. LG: Writing – review & editing. MH: Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing. FM: Investigation, Project administration, Resources, Supervision, Writing – review & editing. FL: Investigation, Project administration, Resources, Supervision, Writing – review & editing. BP: Investigation, Project administration, Resources, Writing – review & editing. PA: Investigation, Supervision, Writing – review & editing. AF: Writing – review & editing. VN: Funding acquisition, Writing – review & editing. RL: Conceptualization, Data curation, Formal Analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. SS: Conceptualization, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Group members of RADAR-MDD-Spain

Peñarrubia-Maria Maria Teresa, Consortium for Biomedical Research in Epidemiology and Public Health (CIBERESP), Instituto de Salud Carlos III, Madrid, Spain, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Gardeñes Moron Lluisa, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Jugo Beatriz, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Orive Cristina, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; De Miguel Blanca, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Blanco Elena, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Gallardo Cristina, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Cobo-Guerrero Silvia, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Molero Aida, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Belvis Mariscal Cristina, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Martinez Gemma, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Valdés Raúl, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Torres-Martinez Rebecca, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; López Fran, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Mera-Cordero Francisco, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Soraluce Acebo Ramón, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Sarró Marta, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Moliner-Molina Cristina, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Flores Maria Rosa, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Sostres Susana, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Ait Ben Aissa, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Poch Marta, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Olmos Maria Cristina, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Ortiz Navarrete Sónia, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Martinez Andrea, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Freixas Olga, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Caldón Beatriz, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Cano Maria Isabel, Unitat de Suport a la Recerca Regió Metropolitana Sud, Fundació Institut Universitari per a la Recerca a l'Atenció Primària de Salut Jordi Gol i Gurina (IDIAPJGol), Barcelona, Spain; Lombardini Federica, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Coromina Marta, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Arranz Belen, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Arranz Sara, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Salvador Laia, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Hernandez Carla, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Marqueta-Marqués Cristina, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Calamardo Elisabet, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Ferenc Tamas, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Rubio-Alacid Elena, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Rojas Antonio, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Druetta Mauro, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Marso Esperança, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Hernandez-Fernandez Elisabet, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Cuñat Oriol, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Otero Begoña, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Tronchoni Mónica, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Tessari Diego, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Labarta Eugenia, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Delisau Yaiza, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Angelats Marina, Research, Innovation and Teaching Unit, Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Spain; Vilella Elisabet, FEA Psicología Clínica, HU Institut Pere Mata, Vendrell, Spain; Llaosa-Scholten Raúl, FEA Psicología Clínica, HU Institut Pere Mata, Vendrell, Spain; Adam Noemí, FEA Psicología Clínica, HU Institut Pere Mata, Vendrell, Spain, Reneses Prieto Blanca, Servicio de Psiquiatría. Hospital Clínico San Carlos, Madrid, Spain; and Zamarro Arranz Maria Luisa, Servicio de Psiquiatría. Hospital Clínico San Carlos, Madrid, Spain.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The RADAR-CNS project received funding from the Innovative Medicines Initiative 2 Joint Undertaking under grant agreement No 115902. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation program and EFPIA (www.imi.europa.eu). This communication reflects the views of the RADAR-CNS consortium and neither IMI nor the European Union and EFPIA are liable for any use that may be made of the information contained herein. RAL received the IHMC22/00003, funded by Instituto de Salud Carlos III and funds Next Generation Eu, which finance the actions of the Recovery and Recovery Mechanism Resilience (MRR). The funding body was not involved in the design, analysis or interpretation of data of this study.

Acknowledgments

Participants in the CIBER site came from the following four clinical communities in Spain: Parc Sanitari Sant Joan de Déu Network services, Institut Catalàde la Salut, InstitutPere Mata, and Hospital Clínico San Carlos. This paper represents independent research partly funded by the National Institute for Health Research NIHR Maudsley Biomedical Research Centre at South London and Maudsley NHS Foundation Trust and King's College London. We thank all the members of the RADAR-CNS patient advisory board for their contribution to the device selection procedures and their invaluable advice throughout the study protocol design. RADAR-MDD will be conducted per the Declaration of Helsinki and Good Clinical Practice, adhering to principles outlined in the NHS Research Governance Framework for Health and Social Care, 2nd edition.

Conflict of interest

PA was employed by H. Lundbeck A/S.

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.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Author disclaimer

The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health and Social Care.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1436611/full#supplementary-material

References

Akhtar-Danesh, N., and Landeen, J. (2007). Relation between depression and sociodemographic factor. *Int. J. Ment. Health. Syst.* 1:4. doi: 10.1186/1752-4458-1-4

Aknin, L. B., Andretti, B., Goldszmidt, R., Helliwell, J. F., Petherick, A., De Neve, J. E., et al. (2022). Policy stringency and mental health during the COVID-19 pandemic: a longitudinal analysis of data from 15 countries. *Lancet Public Health* 7, e417–e426. doi: 10.1016/S2468-2667(22)00060-3

Aluoja, A., Leinsalu, M., Shlik, J., Vasar, V., and Luuk, K. (2004). Symptoms of depression in the Estonian population: prevalence, sociodemographic correlates and social adjustment. *J. Affect. Disord.* 78, 27–35. doi: 10.1016/s0165-0327(02)00179-9

American Psychiatric Association (2013). Diagnostic and statistical manual of mental disorders. *5th* Edn. Arlington, VA: American Psychiatric Association.

Beratis, S., Katrivanou, A., Georgiou, S., Monastirli, A., Pasmatzi, E., Gourzis, P., et al. (2005). Major depression and risk of depressive symptomatology associated with short-term and low-dose interferon-α treatment. *J. Psychosom. Res.* 58, 15–18. doi: 10.1016/j.jpsychores.2004.03.010

Bot, M., Middeldorp, C. M., de Geus, E. J. C., Lau, H. M., Sinke, M., van Nieuwenhuizen, B., et al. (2017). Validity of LIDAS (LIfetime depression assessment self-report): a self-report online assessment of lifetime major depressive disorder. *Psychol. Med.* 47, 279–289. doi: 10.1017/S0033291716002312

Brondino, N., Rocchetti, M., Fusar-Poli, L., Codrons, E., Correale, L., Vandoni, M., et al. (2017). A systematic review of cognitive effects of exercise in depression. *Acta Psychiatr. Scand.* 135, 285–295. doi: 10.1111/acps.12690

Cataluña. Departament d' Interior. (2020). Resolució INT/1433/2020, 18 de junio, n° 8160, de delegació de determinades facultats derivades de l'incompliment de la normativa reguladora de l'estat d'alarma. Diari Oficial de la Generalitat de Catalunya, num 8160. Available at: https://cido.diba.cat/legislacio/10313804/resolucio-int14332020-de-18-de-juny-de-delegacio-de-determinades-facultats-derivades-de-lincompliment-de-la-normativa-reguladora-de-lestat-dalarma-departament-dinterior. (Accessed February 3, 2023)

Cataluña. Departament de Salut. (2020). Resllució SLT/704/2020, d'11 de març, per la qual s'adopten mesures de distanciament social en relació amb els esdeveniments multitudinaris per a la prevenció i el control de la infecció pel SARS-CoV-2. Diari Oficial de la Generalitat de Catalunya, num 8082A. Available at: https://dogc.gencat.cat/ca/document-del-dogc/?documentId=870331. (Accessed February 3, 2023)

COVID-19 Mental Disorders Collaborators (2021). Global prevalence and burden of depressive and anxiety disorders in 204 countries and territories in 2020 due to the COVID-19 pandemic. *Lancet* 398, 1700–1712. doi: 10.1016/S0140-6736(21)02143-7

Currier, D., Lindner, R., Spittal, M. J., Cvetkovski, S., Pirkis, J., and English, D. R. (2020). Physical activity and depression in men: increased activity duration and intensity associated with lower likelihood of current depression. *J. Affect. Disord.* 260, 426–431. doi: 10.1016/j.jad.2019.09.061

de Souza Moura, A. M., Lamego, M. K., Paes, F., Ferreira Rocha, N. B., Simoes-Silva, V., Rocha, S. A., et al. (2015). Comparison among aerobic exercise and other types of interventions to treat depression: a systematic review. *CNS Neurol. Disord. Drug Targets* 14, 1171–1183. doi: 10.2174/1871527315666151111120714

Dishman, R. K., McDowell, C. P., and Herring, M. P. (2021). Customary physical activity and odds of depression: a systematic review and meta-analysis of 111 prospective cohort studies. *Br. J. Sports Med.* 55, 926–934. doi: 10.1136/bjsports-2020-103140

España. Jefatura del Estado (2020). Real Decreto 463/2020, de 14 de marzo, por el que se declara el estado de alarma para la gestión de la situación de crisis sanitaria ocasionada por el COVID-19. *Boletín Oficial Estado* 67, 25390–25400.

España. Ministerio de la Presidencia, Relaciones con las Cortes y Memoria Democrática (2020). Real Decreto 926/2020, de 25 de octubre, por el que se declara el estado de alarma para contener la propagación de infecciones causadas por el SARS-CoV-2. *Boletín Oficial Estado* 282, 91912–91919.

España. Ministerio de Sanidad. (2020a). Orden SND/386/2020, de 3 de mayo, por la que se flexibilizan determinadas restricciones sociales y se determinan las condiciones de desarrollo de la actividad de comercio minorista y de prestación de servicios, así como de las actividades de hostelería y restauración en los territorios menos afectados por la crisis sanitaria ocasionada por el COVID-19. Boletín Oficial del Estado, núm 123, 31103–31112. Available at: https://www.boe.es/eli/es/o/2020/05/03/snd386/con (Accessed March 23, 2023)

España. Ministerio de Sanidad. (2020b). Orden SND/399/2020, de 9 de mayo, para la flexibilización de determinadas restricciones de ámbito nacional, establecidas tras la declaración del estado de alarma en aplicación de la fase 1 del Plan para la transición hacia una nueva normalidad. Boletín Oficial del Estado, núm 130, 31998 a 32026. Available at: https://www.boe.es/eli/es/o/2020/05/09/snd399 (Accessed March 23, 2023)

España. Ministerio de Sanidad. (2020c). Orden SND/414/2020, de 16 de mayo, para la flexibilización de determinadas restricciones de ámbito nacional establecidas tras la declaración del estado de alarma en aplicación de la fase 2 del Plan para la transición hacia una nueva normalidad. Boletín Oficial del Estado, núm 136, 33312 a 33344. Available at: https://www.boe.es/eli/es/o/2020/05/16/snd414 (Accessed: 23 March 2023).

Fitbit Inc. (2018). Fitbit charge 2 user manual. Available at: https://staticcs.fitbit.com/content/assets/help/manuals/manual_charge_2_en_US.pdf (Accessed June 20, 2022)

GBD 2019 Mental Disorders Collaborators (2022). Global, regional, and national burden of 12 mental disorders in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. *Lancet Psychiatry* 9, 137–150. doi: 10.1016/S2215-0366(21)00395-3

Gianfredi, V., Koster, A., Eussen, S. J., Odone, A., Amerio, A., Signorelli, C., et al. (2021). The association between cardio-respiratory fitness and incident depression: the Maastricht study. *J. Affect. Disord.* 279, 484–490. doi: 10.1016/j.jad.2020.09.090

Gill, J. M., Chico, T. J., Doherty, A., Dunn, J., Ekelund, U., Katzmarzyk, P. T., et al. (2023). Potential impact of wearables on physical activity guidelines and interventions: opportunities and challenges. *Br J Sport. Med Mon.* 57, 1223–1225. doi: 10.1136/bjsports-2023-106822

Gómez-Gómez, I., Benítez, I., Bellón, J., Moreno-Peral, P., Oliván-Blázquez, B., Clavería, A., et al. (2023). Utility of PHQ-2, PHQ-8 and PHQ-9 for detecting major depression in primary health care: a validation study in Spain. *Psychol. Med.* 53, 5625–5635. doi: 10.1017/S0033291722002835

Gutiérrez-Rojas, L., Porras-Segovia, A., Dunne, H., Andrade-González, N., and Cervilla, J. A. (2020). Prevalence and correlates of major depressive disorder: a systematic review. *Braz. J. Psychiatry* 42, 657–672. doi: 10.1590/1516-4446-2020-0650

Hale, T., Angrist, N., Goldszmidt, R., Kira, B., Petherick, A., Phillips, T., et al. (2021). A global panel database of pandemic policies (Oxford COVID-19 government response tracker). *Nat. Hum. Behav.* 5, 529–538. doi: 10.1038/s41562-021-01079-8

Hallgren, M., Helgadóttir, B., Herring, M. P., Zeebari, Z., Lindefors, N., Kaldo, V., et al. (2016). Exercise and internet-based cognitive-behavioural therapy for depression: multicentre randomised controlled trial with 12-month follow-up. *Br. J. Psychiatry* 209, 414–420. doi: 10.1192/bjp.bp.115.177576

Hallgren, M., Owen, N., Stubbs, B., Zeebari, Z., Vancampfort, D., Schuch, F., et al. (2018). Passive and mentally-active sedentary behaviors and incident major depressive disorder: a 13-year cohort study. *J. Affect. Disord.* 241, 579–585. doi: 10.1016/j.jad.2018.08.020

Hallgren, M., Vancampfort, D., Owen, N., Rossell, S., Dunstan, D. W., Bellocco, R., et al. (2020). Prospective relationships of mentally passive sedentary behaviors with depression: mediation by sleep problems. *J. Affect. Disord.* 265, 538–544. doi: 10.1016/j.jad.2019.11.088

Hanssen, H., Minghetti, A., Faude, O., Schmidt-Trucksäss, A., Zahner, L., Beck, J., et al. (2018). Effects of endurance exercise modalities on arterial stiffness in patients suffering from unipolar depression: a randomized controlled trial. *Front. Psych.* 8:311. doi: 10.3389/fpsyt.2017.00311

Hardeveld, F., Spijker, J., De Graaf, R., Hendriks, S. M., Licht, C. M., Nolen, W., et al. (2013). Recurrence of major depressive disorder across different treatment settings: results from the NESDA study. *J. Affect. Disord.* 147, 225–231. doi: 10.1016/j.jad.2012.11.008

Hartman, S. J., Nelson, S. H., and Weiner, L. S. (2018). Patterns of Fitbit use and activity levels throughout a physical activity intervention: exploratory analysis from a randomized controlled trial. *JMIR Mhealth Uhealth* 6:e29. doi: 10.2196/mhealth.8503

Kandola, A., Ashdown-Franks, G., Hendrikse, J., Sabiston, C. M., and Stubbs, B. (2019). Physical activity and depression: towards understanding the antidepressant mechanisms of physical activity. *Neurosci. Biobehav. Rev.* 107, 525–539. doi: 10.1016/j.neubiorev.2019.09.040

Kaseva, K., Dobewall, H., Yang, X., Pulkki-Råback, L., Lipsanen, J., Hintsa, T., et al. (2019). Physical activity, sleep, and symptoms of depression in adults-testing for mediation. *Med. Sci. Sports Exerc.* 51, 1162–1168. doi: 10.1249/MSS.0000000000001896

Keating, L. E., Becker, S., McCabe, K., Whattam, J., Garrick, L., Sassi, R. B., et al. (2018). Effects of a 12-week running programme in youth and adults with complex mood disorders. *BMJ Open Sport Exerc. Med.* 4:e000314. doi: 10.1136/bmjsem-2017-000314

Kroenke, K., Strine, T. W., Spitzer, R. L., Williams, J. B., Berry, J. T., and Mokdad, A. H. (2009). The PHQ-8 as a measure of current depression in the general population. *J. Affect. Disord.* 114, 163–173. doi: 10.1016/j.jad.2008.06.026

Krogh, J., Hjorthøj, C., Speyer, H., Gluud, C., and Nordentoft, M. (2017). Exercise for patients with major depression: a systematic review with meta-analysis and trial sequential analysis. *BMJ Open* 7:e014820. doi: 10.1136/bmjopen-2016-014820

Lavalle, R., Condominas, E., Haro, J. M., Giné-Vázquez, I., Bailon, R., Laporta, E., et al. (2023). The impact of COVID-19 lockdown on adults with major depressive disorder from Catalonia: a decentralized longitudinal study. *Int. J. Environ. Res. Public Health* 20:5161. doi: 10.3390/ijerph20065161

Leightley, D., Lavelle, G., White, K. M., Sun, S., Matcham, F., Ivan, A., et al. (2021). Investigating the impact of COVID-19 lockdown on adults with a recent history of recurrent major depressive disorder: a multi-Centre study using remote measurement technology. *BMC Psychiatry* 21:435. doi: 10.1186/s12888-021-03434-5

Leung, W., Case, L., Sung, M. C., and Jung, J. (2022). A meta-analysis of Fitbit devices: same company, different models, different validity evidence. *J. Med. Eng. Technol.* 46, 102–115. doi: 10.1080/03091902.2021.2006350

Lima, R. A., Condominas, E., Sanchez-Niubo, A., Olaya, B., Koyanagi, A., de Miquel, C., et al. (2024). Physical activity participation decreases the risk of depression in older adults: the ATHLOS population-based cohort study. *Sport. Med. Open.* 10, 1–10. doi: 10.1186/S40798-023-00664-7

Matcham, F., di San, B., Pietro, C., Bulgari, V., de Girolamo, G., Dobson, R., et al. (2019). Remote assessment of disease and relapse in major depressive disorder (RADAR-MDD): a multi-Centre prospective cohort study protocol. *BMC Psychiatry* 19:72. doi: 10.1186/s12888-019-2049-z

Matcham, F., Leightley, D., Siddi, S., Lamers, F., White, K. M., Annas, P., et al. (2022). Remote assessment of disease and relapse in major depressive disorder (RADAR-MDD): recruitment, retention, and data availability in a longitudinal remote measurement study. *BMC Psychiatry* 22:136. doi: 10.1186/s12888-022-03753-1

Mathieu, E., Ritchie, H., Rodés-Guirao, L., Appel, C., Giattino, C., Hasell, J., et al. (2020). COVID-19: Stringency index. Our World in Data. Available at: https://ourworldindata.org/covid-stringency-index#learn-more-about-the-data-source-the-oxford-coronavirus-government-response-tracker

Mikkelsen, M. K., Berg-Beckhoff, G., Frederiksen, P., Horgan, G., O'Driscoll, R., Palmeira, A. L., et al. (2020). Estimating physical activity and sedentary behaviour in a free-living environment: a comparative study between Fitbit charge 2 and Actigraph GT3X. *PLoS One* 15:e0234426. doi: 10.1371/journal.pone.0234426

Minghetti, A., Faude, O., Hanssen, H., Zahner, L., Gerber, M., and Donath, L. (2018). Sprint interval training (SIT) substantially reduces depressive symptoms in major depressive disorder (MDD): a randomized controlled trial. *Psychiatry Res.* 265, 292–297. doi: 10.1016/j.psychres.2018.04.053

Nasstasia, Y., Baker, A. L., Lewin, T. J., Halpin, S. A., Hides, L., Kelly, B. J., et al. (2019). Differential treatment effects of an integrated motivational interviewing and exercise intervention on depressive symptom profiles and associated factors: a randomised controlled cross-over trial among youth with major depression. *J. Affect. Disord.* 259, 413–423. doi: 10.1016/j.jad.2019.08.035

Noetel, M., Sanders, T., Gallardo-Gómez, D., Taylor, P., Del Pozo Cruz, B., Van Den Hoek, D., et al. (2024). Effect of exercise for depression: systematic review and network meta-analysis of randomised controlled trials. *BMJ* 384:e075847. doi: 10.1136/BMJ-2023-075847

Pinheiro, J. C., and Bates, D. M. (2000). Mixed-effects models in S and S-PLUS. New York: Springer.

Polhemus, A. M., Novák, J., Ferrao, J., Simblett, S., Radaelli, M., Locatelli, P., et al. (2020). Human-centered design strategies for device selection in mHealth programs: development of a novel framework and Case study. *JMIR Mhealth Uhealth* 8:e16043. doi: 10.2196/16043

R Core Team (2023). R: A language and environment for statistical computing (Versión, 4.3.0) [computer program]. Vienna: R Foundation for Statistical Computing.

Ranjan, Y., Rashid, Z., Stewart, C., Conde, P., Begale, M., Verbeeck, D., et al. (2019). RADAR-base: open source Mobile health platform for collecting, monitoring, and analyzing data using sensors, wearables, and Mobile devices. *JMIR Mhealth Uhealth* 7:e11734. doi: 10.2196/11734

Schuch, F. B., and Stubbs, B. (2019). The role of exercise in preventing and treating depression. *Curr. Sports Med. Rep.* 18, 299–304. doi: 10.1249/JSR.0000000000000620

Schuch, F. B., Vancampfort, D., Firth, J., Rosenbaum, S., Ward, P. B., Silva, E. S., et al. (2018). Physical activity and incident depression: a Meta-analysis of prospective cohort studies. *Am. J. Psychiatry* 175, 631–648. doi: 10.1176/appi.ajp.2018.17111194

Schuch, F. B., Vancampfort, D., Richards, J., Rosenbaum, S., Ward, P. B., and Stubbs, B. (2016a). Exercise as a treatment for depression: a meta-analysis adjusting for publication bias. *J. Psychiatr. Res.* 77, 42–51. doi: 10.1016/j.jpsychires.2016.02.023

Schuch, F. B., Vancampfort, D., Rosenbaum, S., Richards, J., Ward, P. B., Veronese, N., et al. (2016b). Exercise for depression in older adults: a meta-analysis of randomized controlled trials adjusting for publication bias. *Braz. J. Psychiatry* 38, 247–254. doi: 10.1590/1516-4446-2016-1915

Sheikh, M. A., Vancampfort, D., and Stubbs, B. (2018). Leisure time physical activity and future psychological distress: a thirteen year longitudinal population-based study. *J. Psychiatr. Res.* 101, 50–56. doi: 10.1016/j.jpsychires.2018.02.025

Siddi, S., Giné-Vázquez, I., Bailon, R., Matcham, F., Lamers, F., Kontaxis, S., et al. (2022). Biopsychosocial response to the COVID-19 lockdown in people with major depressive disorder and multiple sclerosis. *J. Clin. Med.* 11:7163. doi: 10.3390/jcm11237163

Simblett, S., Matcham, F., Curtis, H., Greer, B., Polhemus, A., Novák, J., et al. (2020). Patients' measurement priorities for remote measurement technologies to aid chronic health conditions: qualitative analysis. *JMIR Mhealth Uhealth* 8:e15086. doi: 10.2196/15086

Simblett, S., Matcham, F., Siddi, S., Bulgari, V., di San, B., Pietro, C., et al. (2019). Barriers to and facilitators of engagement with mHealth Technology for Remote Measurement and Management of depression: qualitative analysis. *JMIR Mhealth Uhealth* 7:e11325. doi: 10.2196/11325

Stevens, M., Lieschke, J., Cruwys, T., Cárdenas, D., Platow, M. J., and Reynolds, K. J. (2021). Better together: how group-based physical activity protects against depression. *Soc. Sci. Med.* 286:114337. doi: 10.1016/j.socscimed.2021.114337

Stubbs, B., Vancampfort, D., Hallgren, M., Firth, J., Veronese, N., Solmi, M., et al. (2018). EPA guidance on physical activity as a treatment for severe mental illness: a meta-review of the evidence and position statement from the European psychiatric association (EPA), supported by the International Organization of Physical Therapists in Mental health (IOPTMH). *Eur. Psychiatry* 54, 124–144. doi: 10.1016/j.eurpsy.2018.07.004

Sun, S., Folarin, A. A., Ranjan, Y., Rashid, Z., Conde, P., Stewart, C., et al. (2020). Using smartphones and wearable devices to monitor behavioral changes during COVID-19. *J. Med. Internet Res.* 22:e19992. doi: 10.2196/19992

Verduijn, J., Verhoeven, J. E., Milaneschi, Y., Schoevers, R. A., van Hemert, A. M., Beekman, A. T. F., et al. (2017). Reconsidering the prognosis of major depressive disorder across diagnostic boundaries: full recovery is the exception rather than the rule. *BMC Med.* 15:215. doi: 10.1186/s12916-017-0972-8

Wagner, S., Wollschläger, D., Dreimüller, N., Engelmann, J., Herzog, D. P., Roll, S. C., et al. (2020). Effects of age on depressive symptomatology and response to antidepressant treatment in patients with major depressive disorder aged 18 to 65 years. *Compr. Psychiatry* 99:152170. doi: 10.1016/j.comppsych.2020.152170

Wolf, S., Seiffer, B., Zeibig, J. M., Welkerling, J., Brokmeier, L., Atrott, B., et al. (2021). Is physical activity associated with less depression and anxiety during the COVID-19 pandemic? A Rapid Systematic Review. *Sports Med.* 51, 1771–1783. doi: 10.1007/S40279-021-01468-Z

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 22 November 2024
DOI 10.3389/fpsyg.2024.1383384

Check for updates

OPEN ACCESS

EDITED BY
Miguel-Angel Gomez-Ruano,
Universidad Politécnica de Madrid, Spain

REVIEWED BY
Andréa Wieck,
Pontifical Catholic University of Rio Grande do Sul, Brazil
Lin Luo,
Guizhou Normal University, China

*CORRESPONDENCE
Fei Shen
✉ doctorfly@jsnu.edu.cn
Yifeng Bu
✉ buyifeng@jsnu.edu.cn

†These authors have contributed equally to this work and share first authorship

RECEIVED 07 February 2024
ACCEPTED 29 October 2024
PUBLISHED 22 November 2024

CITATION
Cui L, Xing Y, Zhou H, Qian J, Li J, Shen F and Bu Y (2024) Physical activity promotes the development of cognitive ability in adolescents: the chain mediating role based on self-education expectations and learning behaviors.
Front. Psychol. 15:1383384.
doi: 10.3389/fpsyg.2024.1383384

Physical activity promotes the development of cognitive ability in adolescents: the chain mediating role based on self-education expectations and learning behaviors

Long Cui[1†], Yumei Xing[2†], Hao Zhou[1], Jia Qian[1], Junnan Li[1], Fei Shen[1*] and Yifeng Bu[1*]

[1]Institute of Physical Education, Jiangsu Normal University, Xuzhou, China, [2]Library, Jiangsu Normal University, Xuzhou, China

Cognitive ability plays a crucial role in adolescents' academic performance and subsequent career development. Although previous studies have demonstrated that physical activity, self-education expectations, and learning behaviors positively affect the cognitive development of adolescents, the extent of their influence and their mediating roles require further elucidation. This study is based on tracking survey data from 2,688 adolescents in Chinese households collected in 2018. Multiple linear regression, Propensity Score Matching, and Quantile regression were employed to analyze the impact and heterogeneity of physical activity on adolescents' cognitive ability. Furthermore, the Bootstrap mediation test was used to explore the mediating roles of self-education expectations and learning behaviors in this process. The results indicate the following: Physical activity significantly promotes adolescents' cognitive ability; for those with poorer cognitive ability, it exerts a greater impact. Moreover, in addition to its direct effects, physical activity indirectly enhances adolescents' cognitive ability through the mediation of three factors (self-education expectations, learning behaviors, self-education expectations and learning behaviors). These discoveries offer significant insights into diverse strategies for developing cognitive ability in adolescents, contributing to both theoretical research and practical interventions.

KEYWORDS

physical activity, self-education expectations, learning behaviors, cognitive ability, adolescents

1 Introduction

Cognitive ability refers to an individual's performance in various mental activities, including memory and recall, attention inhibition and focus, information processing speed, and spatial and causal reasoning (Robinson, 2012). Adolescence is a critical period for the rapid development and high plasticity of cognitive ability (Spear, 2013; Fandakova and Hartley, 2020; Laube et al., 2020), and the cognitive development that occurs during this period greatly benefits future academic performance, behavioral habits, career success, and overall life satisfaction (Heckman, 2007; Carson et al., 2016). Therefore, it is important to explore the factors influencing adolescent cognitive development and the strategies to promote it. Research has shown that, in addition to biological factors such as the growth of the nervous system (Tay et al., 2017), adequate nutrition (Datta et al., 2020), and quality sleep (Chen et al., 2021), social-behavioral factors such as physical activity (Erickson et al., 2019), self-efficacy (Demirtaş, 2019), depressive mood (Vieira et al., 2021), and education (Judd et al., 2022) significantly impact adolescent cognitive ability. Among these, physical activity, self-education expectations, and learning behaviors have attracted significant attention in recent years for their roles in the development of adolescent cognitive function. Existing studies have shown that physical activity can significantly enhance adolescent cognitive function by promoting neural growth in brain regions, improving the antioxidant capacity of brain tissue, and increasing brain activation levels (Marmeleira, 2013). Self-education expectations, as an individual's anticipation of future academic achievements, reflect adolescents' pursuit of academic success and also play an important role in cognitive development. Studies have demonstrated that adolescents with higher self-education expectations and positive learning behaviors often receive more cognitive training, thereby enhancing cognitive ability (Diamond, 2013). However, there is currently a lack of comprehensive research on the interaction mechanisms between physical activity and self-education expectations in relation to adolescent cognitive ability. Additionally, there are widespread concerns that physical activity might encroach on learning time, triggering debates regarding the relationship between physical activity and learning behaviors. Thus, a comprehensive analysis of the interrelationships between physical activity, self-education expectations, and learning behaviors, along with further exploration of their effects on adolescent cognitive development, is of significant theoretical and practical importance.

Furthermore, the relationships among these factors may differ depending on the cultural context. In China, the educational environment and academic demands placed on adolescents differ significantly from those in other countries, particularly with the high emphasis on academic performance and the high expectations from parents and schools, resulting in greater academic pressure on adolescents and fewer opportunities to engage in physical activity. Therefore, exploring the relationships between physical activity, self-education expectations, learning behaviors, and cognitive ability development among adolescents in the Chinese cultural context not only enriches research across diverse cultural backgrounds but also provides scientific evidence for formulating physical activity policies tailored to the realities of Chinese adolescents. It is noteworthy that existing studies often focus on specific age groups or grade levels (Cancela et al., 2019; Fang and Huang, 2021; Shigeta et al., 2021), with few comprehensive studies treating students from different grade levels as a whole. Given that adolescence is a critical period for cognitive ability development and behavioral shaping, conducting systematic analysis by treating upper elementary, middle, and high school students as a continuum of development provides a more comprehensive understanding of the continuity and systematic nature of adolescent cognitive ability development, thereby offering a broader perspective for examining the interplay between physical activity, self-education expectations, and learning behaviors.

Therefore, this study aims to clarify how physical activity, in the Chinese context, promotes the development of adolescents' cognitive ability by enhancing self-education expectations and improving learning behaviors, thereby contributing to the body of research on the impact of physical activity on adolescent cognitive ability.

1.1 Physical activity and cognitive ability

Numerous studies have shown a significant positive correlation between physical activity and the improvement of adolescent cognitive ability. Particularly in Western cultural contexts, multiple cross-sectional studies have demonstrated that higher levels of physical activity are closely related to superior cognitive function and executive abilities (Engeroff et al., 2018; Reigal et al., 2020). Longitudinal studies have also demonstrated similar findings, with one meta-analysis revealing that individuals who engage in higher levels of physical activity experienced a 38% slower rate of cognitive decline over a 12-year follow-up period compared to those who did not participate in physical activity (Sofi et al., 2011). These studies clearly illustrate the long-term protective effect of physical activity on cognitive function. Although research on physical activity and adolescent cognitive development in Western contexts is abundant, related studies based on the Chinese cultural context remain relatively limited and are primarily focused on randomized controlled trials. For example, Chen et al. (2016) showed that a 3-month physical activity intervention significantly improved the executive function of 25 obese adolescents. Similarly, Fu and Fan (2016) conducted an 8-week exercise intervention on 250 adolescents and found that moderate-intensity physical activity significantly improved inhibitory function and shifting ability. These studies suggest that, even in different cultural contexts, physical activity has a significant positive impact on adolescent cognitive ability.

Furthermore, different types of exercise may have varying specific effects on cognitive function. For instance, aerobic exercise is especially effective at improving performance on complex cognitive tasks such as working memory, executive function, and response control, especially in N-back tasks and Stroop tests, where it significantly improves both working memory and information processing speed (Hill et al., 2019). At the same time, resistance training has also shown positive effects on tasks involving selective attention and inhibitory control (Alves et al., 2012). Thus, while different types of physical activity may affect specific components of cognitive function differently, overall, physical activity has a positive effect on cognitive function.

1.2 The mediating role of self-educational expectations

Generally, adolescents engaging in higher levels of physical activity exhibit elevated self-confidence and self-efficacy (Laube et al., 2020), possess increased self-educational expectations (Fredricks and Eccles, 2006), and are more likely to attain greater academic achievement (Donnelly and Lambourne, 2011). Studies indicate that the development of motor skills and athletic accomplishments during physical activity can enhance adolescents' self-worth and self-esteem (Gilani and Dashipour, 2016), which, when transferred to the academic realm, manifest as heightened self-educational expectations. These self-educational expectations further enhance adolescents' efficiency in cognitive exercises and learning processes through motivational activation, ultimately leading to superior cognitive ability in those with higher expectations (Liu et al., 2022). Consequently, therefore, this study hypothesized that self-educational expectations mediate the relationship between physical activity and cognitive ability.

1.3 The mediating role of learning behaviors

Research indicates that cognitive exercise is an effective way to enhance adolescents' cognitive ability, and suggests that the act of learning itself is the most effective method of cognitive exercise. Many parents hold the belief that physical activity not only diminishes adolescents' study time, but also adversely affects their academic engagement (Ferreira Silva et al., 2022), Consequently, they often discourage or even prohibit adolescents from participating in physical activity. However, studies have found that individuals engaging in regular physical activity exhibit a stronger sense of purpose and higher levels of self-discipline. This trait contributes to behavioral habits, thereby promoting more learning behaviors in adolescents (Wilson et al., 2019). This in turn enhances cognitive ability and academic performance (Diamond, 2013). Therefore, this study hypothesized that learning behaviors mediate the relationship between physical activity and cognitive ability.

1.4 Chain-mediated effects of self-educational expectations and learning behaviors

Expectations significantly influence behavior, and an individual's thinking can have a direct impact on the decision-making process and motivation, all of which can affect an individual's behavioral choices (Beckmann and Heckhausen, 2018). Individuals are influenced by subjective thoughts when deciding to engage in a specific behavior, and when the pressure from expectations is perceived, they tend to invest more time in seeking to meet these expectations (Teixeira et al., 2012). Higher self-educational expectations imply encouragement, protection, and recognition of learning-related behaviors, thereby strengthening individuals' engagement in learning (Bates and Anderson, 2014). Consequently, adolescents' self-educational expectations can influence behavioral choices and encourage increased learning behaviors. Physical activity, self-educational expectations, and learning behaviors all influence cognitive ability, and physical activity, in turn, is associated with self-educational expectations and learning engagement. Therefore, this study further hypothesized that Self-educational expectations and learning behaviors exert a chain-mediated effect in physical activity influencing adolescents' cognitive ability.

1.5 The current study

Adolescents' cognitive ability significantly contributes to their academic performance and subsequent career development. Thus, improving adolescents' cognitive ability through approaches grounded in behavioral science and psychology is of paramount importance. Based on an analysis of the relationship between physical activity, self-education expectations, learning behaviors, and adolescent cognitive ability, a chain mediation model was constructed (Figure 1), and four hypotheses were proposed:

> *Hypothesis 1*: Physical activity significantly influences the cognitive ability of adolescents.

> *Hypothesis 2*: Self-education expectations mediate the relationship between physical activity and cognitive ability.

> *Hypothesis 3*: Learning behaviors play a mediating role between physical activity and cognitive ability.

> *Hypothesis 4*: Self-education expectations and learning behaviors exert a chained mediating effect in the process whereby physical activity influences cognitive ability in adolescents.

2 Materials and methods

2.1 Data source and study population

Data was obtained from the China Family Panel Studies (CFPS)[1], a significant survey program conducted by the Institute of Social Sciences at Peking University. The CFPS sample included participants from 25 provinces, municipalities, and autonomous regions in China, representing approximately 95% of the nation's total population. Consequently, the CFPS is considered a nationally representative sample (Xie and Lu, 2015), and the survey received approval from the Biomedical Ethics Committee of Peking University (Approval No.: IRB00001052-14010).

The 2018 China Family Panel Studies (CFPS) data was utilized for this study, as the onset of the COVID-19 pandemic in 2020 led to a reduction in face-to-face interviews, resulting in significant missing cognitive data from that year's CFPS. The database encompassed 37,354 participants, comprising 3,690 adolescents from upper elementary, middle, and high schools. Of these, 691 participants lacked cognitive data and 311 were absent of other study variables. The final sample size that met the study's requirements consisted of 2,688 adolescents aged between 9 and 20.

2.2 Variables

2.2.1 Cognitive ability

The cognitive ability assessment in CFPS 2018 employed vocabulary and math tests designed by the CFPS research team. The CFPS cognitive ability tests have shown high reliability and validity (Qiong and Peihua, 2016) and have been widely validated and applied in previous studies to measure cognitive ability in Chinese adolescents and adults (Zhang et al., 2018; Ren et al., 2019; Li et al., 2021). The CFPS cognitive ability test scale was designed based on the Guttman scale in psychometrics, with testing procedures similar to corresponding subtests of the Wechsler Intelligence Scale, with all vocabulary and math test items drawn from standard Chinese primary and secondary school textbooks (Huang et al., 2015). Specifically, the vocabulary test required respondents to read aloud from one of eight randomly selected vocabulary lists, with each list containing 34 words. The test concluded when the respondent failed to read or misread three consecutive words, or when they completed the 34th word. The final score for the vocabulary test ranged from 0 to 34. In the math

1 www.isss.pku.edu.cn/cfps/

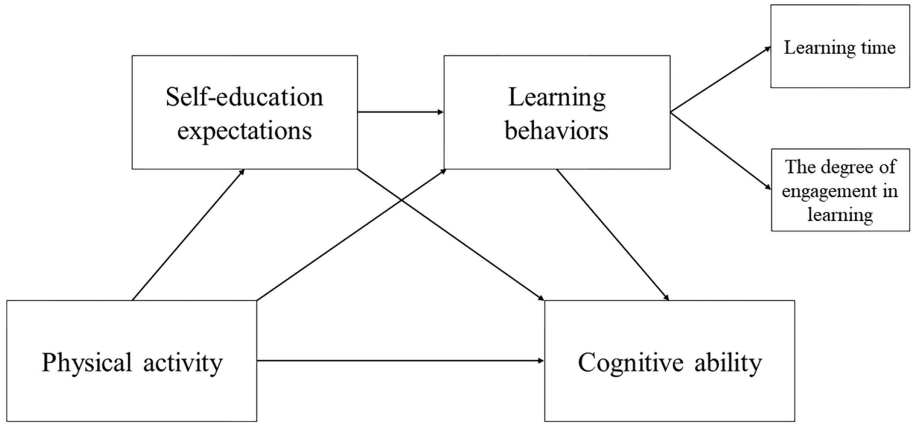


FIGURE 1
The proposed chain-mediation model.

test, respondents randomly selected one of four sets of math problems, which covered topics such as addition, subtraction, multiplication, division, trigonometric functions, and permutations and combinations. The test ended when the respondent failed to answer or answered incorrectly three consecutive questions, or after completing all 24 problems, with the final score ranging from 0 to 24. The total cognitive ability score was the sum of the vocabulary and math test scores, with a range from 0 to 58 (Shi et al., 2022).

2.2.2 Physical activity

Physical activity assessment was based on the average time an individual spent exercising each day. The CFPS survey queried young respondents about their physical activity participation, measuring it through two time-based questions: "Number of times exercised in the past week" and "Total hours exercised in the past week." In accordance with related literature (Zhang, 2023), this study initially excluded outliers, including participants who reported "more than 360 min of exercise per session" and those who had not graduated from elementary school by age 15, middle school by age 18, and high school by age 21. Subsequently, the study calculated the average daily exercise duration in minutes using the formula: Average daily exercise time (minutes) = [Weekly exercise time (minutes)/7], to determine the average daily exercise time for adolescents. In order to make the explanatory variables more consistent with the requirements of normal distribution and to ensure that samples with 0 daily exercise time were not excluded, the study initially incremented the daily exercise time (in minutes) by 1, and subsequently transformed it into a natural logarithm, resulting in the continuous variable that represents adolescents' Physical activity duration (Hu and Yu, 2019; Zhong et al., 2022).

2.2.3 Self-education expectations

In the CFPS survey, respondents were queried about the minimum level of education they believed they should complete. Responses fell into eight categories: "no need to study," "elementary school," "junior high school," "high school," "college," "undergraduate," "master's degree," and "doctoral degree," each response was received a score ranging from 1 to 8, with higher scores indicating greater self-educational expectations.

2.2.4 Learning behaviors

This study, based on existing literature and CFPS data, measures learning behaviors along two dimensions: the first is the "quantity" of learning behaviors, specifically the time spent on learning; the second is the "quality" of learning behaviors, which refers to the degree of engagement in learning (Chen et al., 2015; Wang et al., 2024). Learning time was assessed based on average daily learning time (minutes), and the CFPS survey queried respondents regarding their learning time, primarily measured through two time-dimension questions: "non-weekend learning time" and "weekend learning time." In this paper, the formula employed to calculate the average daily learning time of adolescents is expressed as Average daily learning time (minutes) = ((non-weekend learning time * 5 + weekend learning time * 2)/7). When using this variable, each daily learning time value was first incremented by 1 and then log-transformed to smooth the data. The degree of engagement in learning was evaluated using a self-rating scale consisting of 5 questions, specifically: "I study hard," "I concentrate on my studies in class," "I follow school rules and discipline," "I like to keep my belongings neatly organized at school," and "I only play after I have completed my schoolwork," with ratings ranging from 1 (strongly disagree) to 5 (strongly agree). A higher score indicates a stronger level of agreement. The Cronbach's alpha coefficient for this scale in 2018 was 0.70, indicating acceptable internal consistency for the Learning Engagement Self-Rating Scale. Owing to the large number of missing data for the degree of engagement in learning variable, this paper uses data from the previous period (2016 CFPS survey) to impute missing values, and the sample size of those who answered the degree of engagement in learning question after imputation was 1965.

2.2.5 Control variables

Based on previous studies, this study selects various control variables, encompassing respondents' individual characteristics, family characteristics, and school characteristics. Individual characteristic variables include age, gender (1 for Male, 0 for Female), Residence (0 for rural, 1 for urban), and educational level (1 for elementary school, 2 for junior school, and 3 for senior school), household characteristic variables include parental education level (educational attainment level), household expenditures (expressed as the logarithm). School

TABLE 1 The definition of variables and descriptive statistical results.

Variable name	Variables definition	Mean	SD	N
Cognitive ability	Cognitive ability test scores	38.22	10.39	2,688
Physical activity	Logarithm of average daily physical activity time	2.30	1.79	2,688
Self-education expectations	Level of education	5.36	1.23	2,688
Learning time	Logarithm of average daily learning time	6.03	0.42	2,688
The degree of engagement in learning	The degree of Engagement in Learning Scale Score	22.30	2.99	1965
Age	Age	13.73	2.66	2,688
Gender	Male = 1, Female = 0	0.53	0.50	2,688
Residence	Urban = 1, Rural = 0	0.42	0.49	2,688
Education level	1 = Elementary school, 2 = Junior school, 3 = Senior school	1.79	0.79	2,688
Parental education level	Level of education	3.01	1.18	2,688
Household expenditures	Logarithm of annual household expenditures	10.92	0.79	2,688
School location	1 = Provincial capital city, 2 = General city, 3 = County town, 4 = Countryside	3.21	0.92	2,688
Public School Status	1 = Public school, 0 = Private school	0.91	0.28	2,688
Key School Status	1 = key school, 0 = non-key school	0.25	0.43	2,688
Class size	Number of people in the class	48.13	15.75	2,688
Physical activity status	1 = regular physical activity, 0 = Infrequent physical activity	0.50	0.50	2,688

characteristics cover the school location, whether it is a public school, whether it is a key school and class size. Results for variable naming and descriptive statistics are presented in Table 1. In the regression analysis, all categorical variables are represented as dummy variables.

2.3 Methodology specification

(1) The Ordinary Least Squares (OLS) method was initially employed to estimate the impact of physical activity on cognitive ability. The model was constructed using the following formula:

$$CA_i = a + \beta_1 Exercise_i + \beta_2 Control_i + \epsilon_i \quad (1)$$

In Equation (1), CA_i represents the cognitive ability score of Individual i, $Exercise_i$ represents Individual i's physical activity level, and $Control_i$ denotes the control variable. The term a is the intercept, β_1 is the coefficient for the physical activity variable Exercise, β_2 is the coefficient for the control variable, and ε_i represents the error term.

(2) In sociological research, data often come from observations and surveys. Because many other variables confound the relationship between the independent and dependent variables, interventions are not randomly assigned to study subjects, which can lead to sample selection bias in OLS regression. Specifically in this study, whether individuals engage in physical activity is not randomly assigned but is influenced by a series of covariates (such as gender, age, socioeconomic status), which not only affect the probability of participating in physical activity but may also influence cognitive ability. Even if these covariates are controlled for in OLS regression, estimation bias may still occur due to an imbalance in covariate distribution, affecting the accuracy of estimating the impact of physical activity on cognitive ability. Propensity Score Matching (PSM) can effectively address this issue. The core principle of propensity score matching is to match individuals who received treatment with those who did not, matching individuals with similar propensity scores in the control group. Since potential confounding variables are controlled during matching, the matched treatment and control groups no longer exhibit significant differences in characteristics, thereby reducing selection bias. This process ensures covariate balance between the treatment and control groups, reducing confounding bias due to covariate differences (Haukoos and Lewis, 2015). Therefore, in this study, we use PSM to test the robustness of the OLS model. The model formula is as follows:

$$ATT = E\left\{E\left[CA_{1i}|,D_i = 1|,p\left(x_i\right)\right] - E\left[CA_{0i}|,D_i = 0|,p\left(x_i\right)\right]\right\} \quad (2)$$

In Equation (2), CA_{1i} represents the cognitive ability score of adolescents who regularly engage in physical activity, while CA_{0i} represents the cognitive ability score of adolescents who do not regularly engage in physical activity. When individual i regularly participates in physical activity, $D_i = 1$, otherwise $D_i = 0$. $p(X_i)$ represents the probability of individual i engaging in physical activity. In conducting propensity score matching, the Logit model is first used to calculate the conditional probability, or propensity score, of the treatment group based on the control variables selected in this study. Then, using the estimated propensity scores, individuals in the treatment group who regularly participate in physical activity are matched with individuals in the control group who lack physical activity, ensuring similarity in covariates between the two groups and reducing selection bias. This study employs three commonly used matching methods—nearest neighbor matching, nearest-neighbor matching with caliper, and kernel matching—to estimate the average treatment effect (ATT) of physical activity on cognitive ability. After matching, we evaluate the quality of the matching using two methods: comparing the two-sample *t*-tests of individual covariates and comparing the changes in the kernel density function of propensity scores before and after matching.

(3) Quantile regression was employed to investigate if the impact of physical activity on cognitive ability varies across different cognitive ability distributions. Quantile regression is effective in delineating the impact of explanatory variables on dependent variables at varying quantiles. The model is formulated as follows:

$$Quantile_{\tau}\left(CA\right) = a_{\tau} + \beta_{1\tau}Exercise_i + \beta_{2\tau}Control_i + \epsilon_{i\tau} \qquad (3)$$

In Equation (3), a_{T}, β_{1T}, β_{2T}, and ε_{iT} denote the parameters at the T quantile, respectively.

(4) This study uses the bias-corrected percentile Bootstrap method proposed by Hayes (2017) to test the mediation effect, with 5,000 bootstrap samples. In practice, the Process plugin in SPSS is employed, with model 6 selected, while controlling for covariates at the individual, family, and school levels. Physical activity is used as the independent variable, cognitive ability as the dependent variable, and self-education expectations and learning behaviors as mediating variables to establish a chain mediation model. Hypotheses 2–4 of this study are tested, and when the 95% CI of the test results does not include zero, the mediation effect is considered significant.

3 Results

3.1 The relationship between physical activity and adolescents' cognitive ability

Table 2 presents the OLS regression results. Model (1) includes only the core variables: physical activity and individual characteristics. The parameter estimate of β1 in Model (1) is estimated at 0.354 ($p < 0.01$), suggesting that physical activity significantly influences cognitive ability. Models (2) and (3) extend the analysis by including family and school characteristics, with the parameter estimate of β1 at 0.273 ($p < 0.01$), suggesting a 0.273-point increase in cognitive ability for every 1% increase in physical activity time. Furthermore, the R^2 value of the regression increased from 0.468 to 0.496, demonstrating an enhanced ability of the model to explain variations in adolescents' cognitive ability due to the inclusion of family and School characteristics. Consequently, Hypothesis H1 is confirmed.

3.2 Heterogeneity in the effects of physical activity on adolescents' cognitive ability

3.2.1 Robustness tests for the role of physical activity: estimation based on the PSM

To estimate the net effect of physical activity on cognitive ability, this study employed the propensity score matching (PSM) method to mitigate potential sample selectivity bias that could undermine the reliability of the results. This study defined adolescents participating in physical activity three or more times per week as the "regular physical activity" treatment group, and those with less than three weekly sessions as the "physically inactive" control group (Fang and Huang, 2021). Physical activity was converted into a 0, 1 dummy variable (1 for the treatment group, 0 for the control group), thus satisfying the requirements of the Propensity Score Matching method for the variable.

The study used two methods to test for match quality. First, two-sample t-tests for individual covariates were conducted. The results showed that after propensity score matching, the standardized deviations of all variables were less than 10% and there was no significant difference after matching ($p > 0.1$). This shows that the propensity score matching method solves the sample selectivity bias problem to a large extent. Then compare the changes in the kernel density function distribution of the propensity score values before and after matching. Figure 2 shows the kernel density function plots before and after sample matching. From the figure, it can be observed that the difference in the probability distribution of the propensity score values of the treatment group and the control group after matching is narrowed, the common range of values is wider, and the trend of the curves tends to be more consistent. It indicates that the matching effect is well.

In order to accurately estimate the Average Treatment Effect of Treated on adolescents' cognitive ability by regular participation in physical activity, three matching methods were used in this study for the test: nearest-neighbor matching ($k = 2$), nearest-neighbor matching with caliper ($k = 2$; $r = 0.01$), and kernel matching (default kernel function and bandwidth). The results showed that regular participation in physical activity consistently contributes significantly to the cognitive ability of adolescents, with effect values ranging from 0.802 to 1.117 (Table 3). The results of all three matching methods are significant at the 5% statistical level, which indicates the robustness of the results obtained through propensity score matching.

3.2.2 The relationship between physical activity and cognitive ability in adolescents: the influence of individual cognitive level

The Ordinary Least Squares (OLS) analysis quantifies the average effect of physical activity on cognitive ability. To delve into potential differences in the impact of physical activity on students with varying cognitive ability and their distinct manifestations, quantile regression

TABLE 2 The relationship between physical activity and adolescents' cognitive ability: results of OLS.

Variables	Model (1)	Model (2)	Model (3)
Physical activity	0.354*** (0.083)	0.268*** (0.081)	0.273*** (0.081)
Individual characteristics	Control	Control	Control
Family characteristics		Control	Control
School characteristics			Control
Constant	9.149*** (1.139)	3.298 (2.323)	4.365* (2.645)
R^2	0.468	0.491	0.496

$N = 2,688$, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Standard errors are in parentheses.

was utilized to examine the heterogeneity in the effects of physical activity.

The estimates indicate that the impact of physical activity on cognitive ability, across the 0.1, 0.25, 0.5, 0.75, and 0.9 quartiles, are 0.394 ($p < 0.1$), 0.329 ($p < 0.01$), 0.326 ($p < 0.01$), 0.198 ($p < 0.01$), and 0.118 ($p < 0.1$), respectively (Table 4). According to the estimates across different cognitive ability quartiles, the impact of physical activity on cognitive ability is more pronounced for individuals in the lower cognitive quartiles than those in the higher quartiles (Figure 3), suggesting that adolescents with lower cognitive ability benefit more substantially from physical activity, and the duration of such activity is positively correlated with the extent of cognitive enhancement. Therefore, it is significant to encourage and guide adolescents with lower cognitive ability to actively engage in physical activity, as it promotes cognitive development within this demographic.

3.3 Chain mediation analysis of self-educational expectations and learning behaviors

Given that this study categorizes learning behaviors into two dimensions: "quantity" referring to learning time, and "quality" indicating the degree of engagement in learning, the mediation analysis should accordingly be conducted in two distinct segments: learning time and the degree of engagement in learning.

3.3.1 Chain mediation analysis of self-education expectations and learning time

The results reveal that physical activity exerts a direct effect on cognitive ability, with an estimated impact of 0.1999 (CI: 0.0453–0.3545), after controlling for covariates, contributing to 73.223% of the total effect. The estimated parameter for the indirect effect of physical activity on cognitive ability, mediated by self-educational expectations and learning time, is 0.0730 (CI: 0.0332–0.1205), representing 26.740% of the total effect. The mediation analysis reveals that self-education expectation (physical activity path → self-education expectation path → cognitive ability path) constitutes 12.857% (CI: 0.0119–0.0615) of the total effect, signifying a significant mediation in the relationship between physical activity and cognitive ability, thereby confirming Hypothesis H2. Learning time's mediating effect (physical activity pathway → learning time pathway → cognitive ability pathway) was found to be 11.538% (CI: 0.0028–0.0673), underscoring its significant role in mediating the relationship between physical activity and cognitive ability. The combined mediation of self-education expectation and learning time (physical activity path → self-education expectation path → learning time path → cognitive ability path) contributed to 2.381% (CI: 0.0021–0.0121) of the effect, indicating a chained mediating role for self-educational expectations and learning time. Table 5 and Figure 4 display the mediation analysis results.

3.3.2 Chain mediation of self-educational expectations and the degree of engagement in learning

The mediation effect of the degree of engagement in learning (physical activity path → the degree of engagement in learning path → cognitive ability path) constitutes 12.370% of the overall mediation effect (CI: 0.0083–0.0644), indicating significant mediation by the degree of engagement in learning between physical activity and cognitive ability (Table 6 and Figure 5). Given that the mediation effects of both learning time and the degree of engagement in learning are validated, Hypothesis H3 is confirmed. The combined mediation effect of self-education expectation and learning time (physical activity path → self-education expectations path → the degree of engagement in learning path → cognitive ability path) was 0.594% (CI: 0.0001–0.0044), suggesting that self-educational expectations and the degree of engagement in learning exert chained mediating effects. Given the chain mediating effects of self-educational expectations with both learning time and the degree of engagement in learning are valid, Hypothesis H4 is substantiated.

Given the partial missing data for the degree of engagement in learning variable ($n = 1965$), slight discrepancies exist between the data in Table 6 and Figure 5, and those in Table 5 and Figure 4, yet these minor discrepancies also suggest that the missing data for the degree of engagement variable occurs completely at random, not compromising the overall data credibility.

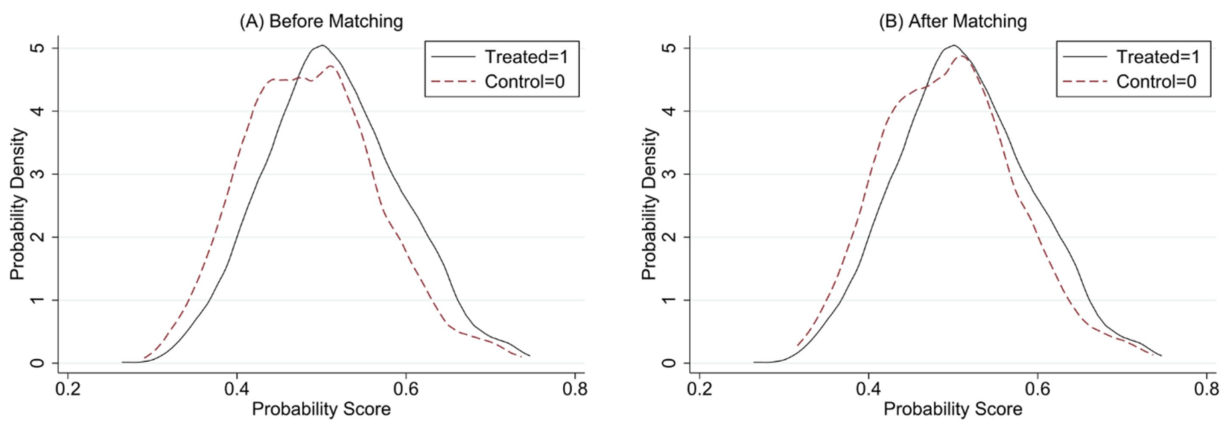


FIGURE 2
Kernel function plot before and after sample matching. The solid line represents the treatment group, and the dashed line represents the control group.

4 Discussion

4.1 Effects of physical activity on cognitive ability

The findings of the study demonstrate that, after controlling for the variables of individual characteristics, family characteristics and school characteristics, physical activity exerts a significant impact on adolescents' cognitive ability, and that every 1% increment in physical activity time leads to a 0.273-point enhancement in cognitive ability, corresponding to 0.714% of the average cognitive ability. Considering the issue of sample selection bias, this study employs the Propensity Score Matching method to address potential endogeneity, with the results indicating that the positive impact of physical activity on adolescents' cognitive ability is robust. This aligns with the conclusions of prior research (Guan and Tena, 2022). An additional significant discovery is the heterogeneity in the impact of physical activity on cognitive ability, as revealed by Quantile regression analysis. This analysis demonstrates that adolescents with lower cognitive ability experience greater benefits from engaging in physical activity, indicating that those at a cognitive disadvantage gain more from physical activity. This diverges from prior findings, which identified the most substantial facilitating effects of physical activity on adolescents with median cognitive ability (Fang and Huang, 2021), and this discrepancy could be due to the younger average age of the samples used in this study. Adolescents, owing to variations in neurological development rates, are more likely to exhibit gaps in cognitive ability, which physical activity can help mitigate. This study illustrates that physical activity more significantly benefits adolescents with lower cognitive ability, highlighting the importance of physical activity in bridging developmental cognitive gaps.

In practice, adolescents with lower cognitive ability are disadvantaged along with those with lower academic performance. If an activity is particularly beneficial to the group possessing disadvantaged cognitive ability, this indicates that such an activity fosters cognitive equity and, consequently, educational equity. This study clearly demonstrates that physical activity fulfills such a role, making the promotion of physical activity among adolescents, particularly those with disadvantaged cognitive ability, not only beneficial for their physical health but also crucially important for enhancing their cognitive ability.

TABLE 3 The relationship between physical activity and adolescents' cognitive ability: results of PSM estimation.

Matching method	T	C	ATT	Standard errors
Nearest-neighbor matching	38.737	37.620	1.117**	0.477
Nearest-neighbor matching with caliper	38.737	37.620	1.117**	0.477
Kernel matching	38.741	37.939	0.802**	0.410

$N = 2{,}688$, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, nearest-neighbor matching ($k = 2$), nearest-neighbor matching with caliper ($k = 2$; $r = 0.01$), kernel matching (default kernel function and bandwidth).

4.2 The mediating role of self-education expectations

This study shows that self-education expectations play an independent mediating role between physical activity and adolescent cognitive development. This result is consistent with previous studies, which indicate that adolescents who regularly engage in physical activity tend to have higher educational expectations (Kim and Park, 2015), and higher educational expectations are closely related to enhanced cognitive ability (Liu et al., 2022). From a psychological perspective, self-efficacy theory (Bandura, 1977) provides a theoretical foundation for this phenomenon. The theory suggests that physical activity can enhance adolescents' sense of self-efficacy, or confidence in their own abilities (Fu et al., 2023). This increased sense of self-efficacy helps lower-achieving adolescents develop a positive self-perception, which extends to their academic expectations, thereby raising their educational expectations. The heightened educational expectations, through pathways such as motivation activation (Brandstätter and Bernecker, 2022) and attention regulation (Anderson, 2013), not only increase adolescents' likelihood of participating in cognitive activities but also enhance their efficiency in these activities, ultimately promoting the development of their cognitive ability.

4.3 The mediating role of learning behaviors

This study found that learning behaviors also play an independent mediating role between physical activity and cognitive ability. Previous studies have shown that physical activity helps improve learning

TABLE 4 Quantile regression of physical activity on adolescents' cognitive ability.

Variables	$\tau = 0.1$	$\tau = 0.25$	$\tau = 0.5$	$\tau = 0.75$	$\tau = 0.9$
Physical activity	0.394* (0.235)	0.329*** (0.125)	0.326*** (0.085)	0.198*** (0.073)	0.118* (0.060)
Individual characteristics	Control	Control	Control	Control	Control
Family characteristics	Control	Control	Control	Control	Control
School characteristics	Control	Control	Control	Control	Control
Constant	−12.476* (6.484)	−6.274 (4.239)	2.854 (2.447)	10.722*** (2.241)	19.852*** (2.853)
R^2	0.245	0.294	0.354	0.375	0.404

$N = 2{,}688$, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Standard errors are in parentheses.

behaviors (Harvey et al., 2018). However, in real life, students, parents, and society often worry that physical activity will take up study time (Ferreira Silva et al., 2022). The results of this study suggest that this concern may be a stereotype. The notion that physical activity reduces study time may be a subjective perception of students and parents. In reality, physical activity often takes up time outside of study hours. For instance, studies have shown that moderate physical activity significantly reduces the time students spend on online games (Li and Jiang, 2023). Therefore, proper scheduling of physical activity not only avoids reducing effective study time but can also improve learning behaviors by reducing time wasted on non-essential activities, thereby increasing the frequency and quality of cognitive activities.

Physiological psychology suggests that changes in brain function are inseparable from physiological changes. Physical activity promotes the secretion of brain-derived neurotrophic factor (BDNF), enhancing the plasticity of brain regions related to learning and memory, such as the hippocampus (Phillips, 2017). This physiological change provides a neural basis for more efficient learning behaviors, improving adolescents' attention control, information processing, and memory during the learning process. During adolescence, cognitive ability is highly plastic, and learning behaviors are one of the key ways to promote cognitive development (Kolinsky, 2015). Therefore, physical activity not only directly strengthens the neural basis of adolescents' learning behaviors through physiological mechanisms but also indirectly enhances the "quality" and "quantity" of learning through psychological pathways, such as increasing self-education expectations. As learning behaviors continue to improve, adolescents' cognitive ability is also significantly enhanced.

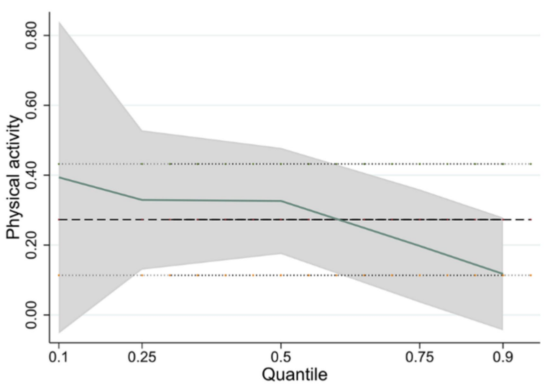


FIGURE 3
Changes in the physical activity at different percentiles of cognitive ability.

4.4 Chain mediation of self-educational expectations and learning behaviors

This study shows that physical activity can influence cognitive ability through a chain mediation of self-education expectations and learning behaviors. Previous studies have shown that physical activity helps adolescents build confidence and a positive self-image (Aceves et al., 2020), and this positive sense of self-worth and self-image can enhance their educational expectations. Self-education expectations, as a key psychological factor, not only influence individuals' goal-setting but also have a profound impact on their behavioral choices. High levels of self-education expectations can continuously motivate individuals in the learning process, strengthening their learning behaviors and thereby enhancing cognitive ability (Hattie et al., 2020). Additionally, studies have found that a lack of physical activity is closely related to cognitive decline (Aichberger et al., 2010), and a reduction in learning behaviors further exacerbates this effect (Zacharopoulos et al., 2021). These findings clearly demonstrate the important roles that self-education expectations and learning behaviors play between physical activity and cognitive ability.

While many studies have focused on fitness factors as key mediators of the effect of physical activity on cognitive ability (Ruiz-Hermosa et al., 2020; Hernández-Jaña et al., 2021), such as the positive effects of aerobic and strength training on fluid intelligence, particularly by promoting the secretion of brain-derived neurotrophic factor (BDNF), enhancing angiogenesis, and synaptogenesis, thereby improving the plasticity of brain regions related to cognitive function (Augusto-Oliveira et al., 2023), this study mainly focuses on the development of crystallized intelligence, a cognitive domain that relies more on the accumulation of learning experiences. Therefore, learning behaviors play a crucial role in the influence of physical activity on cognitive ability. The improvement of crystallized intelligence depends on a continuous learning process, and focusing solely on the direct effects of physical activity while ignoring the role of learning behaviors makes it difficult to establish a clear causal relationship between physical activity and crystallized intelligence.

In conclusion, the main contribution of this study is that it is the first to reveal self-education expectations and learning behaviors as important mediating factors in the promotion of cognitive ability (particularly crystallized intelligence) by physical activity, providing

TABLE 5 Mediating role of self-educational expectations and learning time in the relationship between physical activity and cognitive ability.

Effect	Estimate	BootSE	BootLLCI	BootULCI	Effect value (%)
Total effect (physical activity)	0.2730	0.0812	0.1136	0.4323	
Direct effect (physical activity)	0.1999	0.0788	0.0453	0.3545	73.223%
Indirect effect (self-education expectation)	0.0351	0.0127	0. 0119	0.0615	12.857%
Indirect effect (learning time)	0.0315	0.0162	0.0028	0.0673	11.538%
Indirect effect (self-education expectation and learning time)	0.0065	0.0026	0.0021	0.0121	2.381%
Total indirect effect of mediators	0.0730	0.0221	0.0332	0.1205	26.740%

N = 2,688, BootSE represents the standard error, BootLLCI and BootULCI denote the lower and upper bounds, respectively, of the indirect effect within the 95% confidence interval, as estimated by the bias-corrected percentile Bootstrap method.

10.3389/fpsyg.2024.1383384

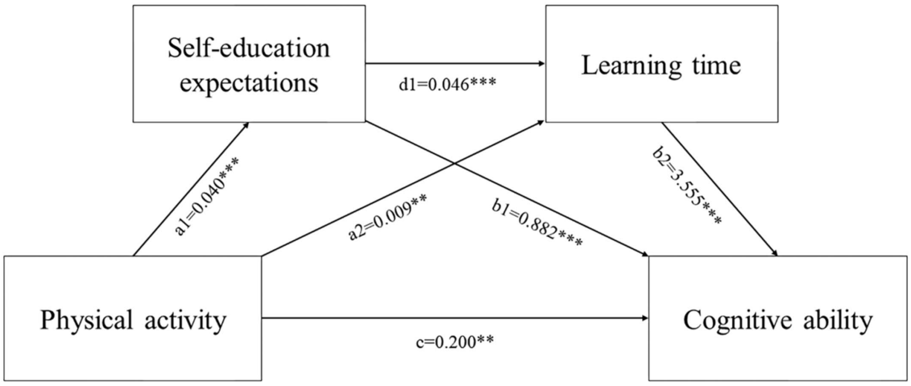


FIGURE 4
The mediation model of self-educational expectations and learning time as mediators between physical activity and cognitive ability. ****p* < 0.01, ****p* < 0.05, **p* < 0.1, the mediating effect of self-educational expectations on the relationship between physical activity and cognition is denoted as a1*b1; the mediating effect of learning time, as a2*b2; the combined mediating effect of educational expectations and learning time, as a1*d1*b2. The total effect of physical activity on cognition is represented by a1*b1+a2*b2+a1*d1*b2+c.

TABLE 6 Mediating role of self-educational expectations and the degree of engagement in learning in the relationship between physical activity and cognitive ability.

Effect	Estimate	BootSE	BootLLCI	BootULCI	Effect value (%)
Total effect (physical activity)	0.2692	0.0918	0.0892	0.4492	
Direct effect (physical activity)	0.1954	0.0908	0 0.0174	0.3734	72.585%
Indirect effect (self-education expectation)	0.0388	0.0180	0. 0045	0.0774	14.413%
Indirect effect (the degree of engagement in learning)	0.0333	0.0145	0.0083	0.0644	12.370%
Indirect effect (self-education expectation and the degree of engagement in learning)	0.0016	0.0011	0.0001	0.0044	0.594%
Total indirect effect of mediators	0.0738	0.0241	0.0278	0.1228	27.415%

N = 2,688, BootSE represents the standard error, BootLLCI and BootULCI denote the lower and upper bounds, respectively, of the indirect effect within the 95% confidence interval, as estimated by the bias-corrected percentile Bootstrap method.

a new theoretical perspective on how physical activity influences adolescent cognitive development through psychological and behavioral pathways.

4.5 Implications, limitations and future research

This study confirmed the positive effects of physical activity on adolescents' cognitive ability and revealed the mediating roles of self-education expectations and learning behaviors, providing valuable insights for both theoretical and practical research on improving adolescents' cognitive ability. However, this study has certain limitations. First, although it is based on a large and representative sample from a questionnaire survey, selection bias may still exist compared to randomized controlled trials, and the use of propensity score matching (PSM) does not fully eliminate this issue. Future research should adopt more rigorous experimental controls to better address sample selection bias. Second, the questionnaire did not specifically distinguish between the time spent on different types of physical activity, making it difficult to compare the specific effects of various types of physical activity on cognitive ability, which represents a limitation of this study. Therefore, future research should further explore the differential effects of exercise intensity, total load, and different types of physical activity on cognitive ability, in order to more comprehensively examine the mediating roles of self-education expectations and learning behaviors between physical activity and cognitive ability.

5 Conclusion

This study shows that physical activity can significantly promote the development of cognitive ability in adolescents. However, the effects of physical activity vary across different groups, with cognitive improvement being more pronounced among adolescents with weaker cognitive ability. In addition to its direct effects, physical activity can also indirectly influence adolescents' cognitive ability through three mediating pathways: self-education expectations, learning behaviors, and the chain mediation of self-education expectations and learning behaviors. This study, based on a nationally representative sample of Chinese adolescents, explores the role of physical activity in promoting cognitive ability development. The results not only provide strong theoretical support for the formulation of policies aimed at

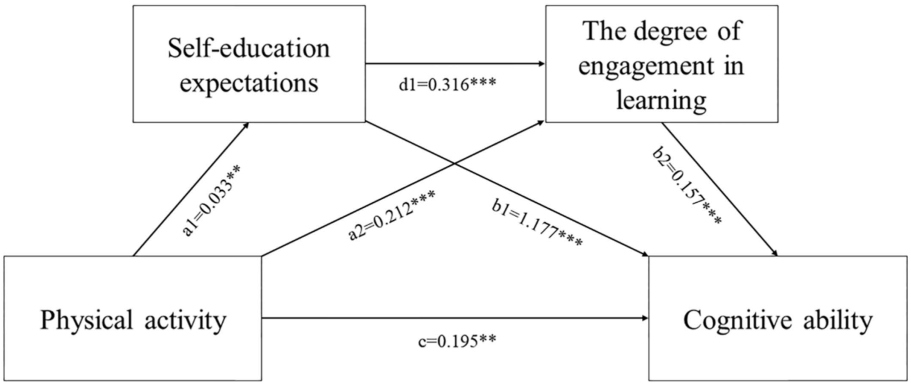


FIGURE 5
The mediation model of self-educational expectations and the degree of engagement in learning as mediators between physical activity and cognitive ability. ***p < 0.01, ***p < 0.05, *p < 0.1, the mediating effect of self-educational expectations on the relationship between physical activity and cognition is denoted as a1*b1; the mediating effect of the degree of engagement in learning, as a2*b2; the combined mediating effect of educational expectations and the degree of engagement in learning, as a1*d1*b2. The total effect of physical activity on cognition is represented by a1*b1 + a2*b2 + a1*d1*b2 + c.

enhancing the cognitive ability of Chinese adolescents but also offer valuable insights for youth sports education practices across various cultural contexts globally. Future research should delve deeper into the specific mechanisms through which different types of physical activities influence cognitive development, to more precisely validate the effects of physical activity and further clarify the mediating roles of self-education expectations and learning behaviors in this process. Additionally, it is worth further investigating how to optimize the effectiveness of physical activity in promoting cognitive development, and its influencing factors, across different social and cultural contexts.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: http://www.isss.pku.edu.cn/cfps/.

Ethics statement

The studies involving humans were approved by the Biomedical Ethics Committee of Peking University. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

LC: Data curation, Project administration, Software, Writing – original draft. YX: Conceptualization, Methodology, Resources, Visualization, Writing – original draft. HZ: Conceptualization, Writing – review & editing. JQ: Writing – review & editing. JL: Writing – review & editing. FS: Supervision, Writing – review & editing. YB: Funding acquisition, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by the Youth Fund for Humanities and Social Sciences Research of the Ministry of Education (22YJC890023), the Key Project of "2022 Higher Education Scientific Research Planning Project" of China Association of Higher Education (22TY0218), the Research Program for Excellent Doctoral Degree Teachers of JSNU (21XFRX015), the Second Batch of Undergraduate Education and Teaching Reform Research Projects during the 14th Five-Year Plan of JSNU (JYKTY202321), the Jiangsu Universities "Youth and Blue Project" Funding Program and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX24_3038).

Acknowledgments

Thanks to CFPS for the detailed and credible data.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aceves, L., Bámaca-Colbert, M. Y., and Robins, R. W. (2020). Longitudinal linkages among parents' educational expectations, Youth's educational expectations, and competence in Mexican-origin families. *J Youth Adolescence* 49, 32–48. doi: 10.1007/s10964-019-01161-5

Aichberger, M. c., Busch, M. a., Reischies, F. m., Ströhle, A., Heinz, A., and Rapp, M. a. (2010). Effect of physical inactivity on cognitive performance after 2.5 years of follow-up. *GeroPsych* 23, 7–15. doi: 10.1024/1662-9647/a000003

Alves, C. R., Gualano, B., Takao, P. P., Avakian, P., Fernandes, R. M., Morine, D., et al. (2012). Effects of acute physical exercise on executive functions: a comparison between aerobic and strength exercise. *J. Sport Exerc. Psychol.* 34, 539–549. doi: 10.1123/jsep.34.4.539

Anderson, B. A. (2013). A value-driven mechanism of attentional selection. *J. Vis.* 13:7. doi: 10.1167/13.3.7

Augusto-Oliveira, M., Arrifano, G. P., Leal-Nazaré, C. G., Santos-Sacramento, L., Lopes-Araújo, A., Royes, L. F. F., et al. (2023). Exercise reshapes the brain: molecular, cellular, and structural changes associated with cognitive improvements. *Mol. Neurobiol.* 60, 6950–6974. doi: 10.1007/s12035-023-03492-8

Bandura, A. (1977). Self-efficacy: toward a unifying theory of behavioral change. *Psychol. Rev.* 84, 191–215. doi: 10.1037/0033-295X.84.2.191

Bates, L. A., and Anderson, P. D. (2014). Do expectations make the difference? A look at the effect of educational expectations and academic performance on enrollment in post-secondary education. *Race Soc. Probl.* 6, 249–261. doi: 10.1007/s12552-014-9126-1

Beckmann, J., and Heckhausen, H. (2018). "Motivation as a function of expectancy and incentive" in Motivation and Action. *3rd Edn*. eds. J. Heckhausen and H. Heckhausen (Cham: Springer), 163–220.

Brandstätter, V., and Bernecker, K. (2022). Persistence and disengagement in personal goal pursuit. *Annu. Rev. Psychol.* 73, 271–299. doi: 10.1146/annurev-psych-020821-110710

Cancela, J., Burgo, H., and Sande, E. (2019). Physical fitness and executive functions in adolescents: cross-sectional associations with academic achievement. *J. Phys. Ther. Sci.* 31, 556–562. doi: 10.1589/jpts.31.556

Carson, V., Hunter, S., Kuzik, N., Wiebe, S. A., Spence, J. C., Friedman, A., et al. (2016). Systematic review of physical activity and cognitive development in early childhood. *J. Sci. Med. Sport* 19, 573–578. doi: 10.1016/j.jsams.2015.07.011

Chen, S.-R., Tseng, C.-L., Kuo, S.-Y., and Chang, Y.-K. (2016). Effects of a physical activity intervention on autonomic and executive functions in obese young adolescents: a randomized controlled trial. *Health Psychol.* 35, 1120–1125. doi: 10.1037/hea0000390

Chen, Y., Wang, Y., Wang, S., Zhang, M., and Wu, N. (2021). Self-reported sleep and executive function in early primary school children. *Front. Psychol.* 12:12. doi: 10.3389/fpsyg.2021.793000

Chen, L. J., Yang, D. L., and Ren, Q. (2015). Report on the state of children in China. Chicago: Chapin Hall at the University of Chicago.

Datta, N., Bidopia, T., Datta, S., Mittal, G., Alphin, F., Marsh, E. J., et al. (2020). Meal skipping and cognition along a spectrum of restrictive eating. *Eat. Behav.* 39:101431. doi: 10.1016/j.eatbeh.2020.101431

Demirtaş, A. S. (2019). Cognitive flexibility and mental well-being in Turkish adolescents: the mediating role of academic, social and emotional self-efficacy. *An Psicol. Spain* 36, 111–121. doi: 10.6018/analesps.336681

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Donnelly, J. E., and Lambourne, K. (2011). Classroom-based physical activity, cognition, and academic achievement. *Prev. Med.* 52, S36–S42. doi: 10.1016/j.ypmed.2011.01.021

Engeroff, T., Ingmann, T., and Banzer, W. (2018). Physical activity throughout the adult life span and domain-specific cognitive function in old age: a systematic review of cross-sectional and longitudinal data. *Sports Med.* 48, 1405–1436. doi: 10.1007/s40279-018-0920-6

Erickson, K. I., Hillman, C., Stillman, C. M., Ballard, R. M., Bloodgood, B., Conroy, D. E., et al. (2019). Physical activity, cognition, and brain outcomes: a review of the 2018 physical activity Guidelines. *Med. Sci. Sports Exerc.* 51, 1242–1251. doi: 10.1249/MSS.0000000000001936

Fandakova, Y., and Hartley, C. A. (2020). Mechanisms of learning and plasticity in childhood and adolescence. *Dev. Cogn. Neurosci.* 42:100764. doi: 10.1016/j.dcn.2020.100764

Fang, C., and Huang, B. (2021). Can physical exercise promote the development of teenagers' cognitive ability? An empirical study based on CEPS. *J. East China Normal Univ.* 39:84. doi: 10.16382/j.cnki.1000-5560.2021.03.008

Ferreira Silva, R. M., Mendonça, C. R., Azevedo, V. D., Raoof Memon, A., Noll, P. R. E. S., and Noll, M. (2022). Barriers to high school and university students' physical activity: a systematic review. *PLoS One* 17:e0265913. doi: 10.1371/journal.pone.0265913

Fredricks, J. A., and Eccles, J. S. (2006). Is extracurricular participation associated with beneficial outcomes? Concurrent and longitudinal relations. *Dev. Psychol.* 42, 698–713. doi: 10.1037/0012-1649.42.4.698

Fu, J., and Fan, Y. (2016). Experimental study on the influence of moderate-intensity physical exercise on executive function and academic performance of junior high school students at different times. *Sports Sci* 37, 110–116. doi: 10.13598/j.issn1004-4590.2016.06.016

Fu, W., Li, Y., Liu, Y., Li, D., Wang, G., Liu, Y., et al. (2023). The influence of different physical exercise amounts on learning burnout in adolescents: the mediating effect of self-efficacy. *Front. Psychol.* 14:1089570. doi: 10.3389/fpsyg.2023.1089570

Guan, J., and Tena, J. D. (2022). Physical activity, leisure-time, cognition and academic grades: connections and causal effects in Chinese students. *J. Asian Econ.* 78:101423. doi: 10.1016/j.asieco.2021.101423

Harvey, S. P., Lambourne, K., Greene, J. L., Gibson, C. A., Lee, J., and Donnelly, J. E. (2018). The effects of physical activity on learning behaviors in elementary school children: a randomized controlled trial. *Contemp School Psychol* 22, 303–312. doi: 10.1007/s40688-017-0143-0

Hattie, J., Hodis, F. A., and Kang, S. H. K. (2020). Theories of motivation: integration and ways forward. *Contemp. Educ. Psychol.* 61:101865. doi: 10.1016/j.cedpsych.2020.101865

Haukoos, J. S., and Lewis, R. J. (2015). The propensity score. *JAMA* 314, 1637–1638. doi: 10.1001/jama.2015.13480

Hayes, A. F. (2017). Introduction to mediation, moderation, and conditional process analysis: a regression-based approach. New York, NY: Guilford Publications.

Heckman, J. J. (2007). The economics, technology, and neuroscience of human capability formation. *Proc. Natl. Acad. Sci. USA* 104, 13250–13255. doi: 10.1073/pnas.0701362104

Hernández-Jaña, S., Sanchez-Martinez, J., Solis-Urra, P., Esteban-Cornejo, I., Castro-Piñero, J., Sadarangani, K. P., et al. (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.* 15:15. doi: 10.3389/fnbeh.2021.746197

Hill, M. D., Gibson, A.-M., Wagerman, S. A., Flores, E. D., and Kelly, L. A. (2019). The effects of aerobic and resistance exercise on state anxiety and cognitive function. *Sci. Sports* 34, 216–221. doi: 10.1016/j.scispo.2018.09.004

Hu, P., and Yu, F. (2019). A study about the restrictive factors on physical exercise of the middle school students—an HLM model based on CEPS (2014-2015). *China Sport Sci* 39, 76–84. doi: 10.16469/j.css.201901010

Huang, G., Xie, Y., and Xu, H. (2015). Cognitive ability: social correlates and consequences in contemporary China. *Chin. Sociol. Rev.* 47, 287–313. doi: 10.1080/21620555.2015.1032161

Judd, N., Sauce, B., and Klingberg, T. (2022). Schooling substantially improves intelligence, but neither lessens nor widens the impacts of socioeconomics and genetics. *npj Sci. Learn* 7:33. doi: 10.1038/s41539-022-00148-5

Kim, C. R., and Park, P. (2015). The relationship among physical activities participation, social Capital in Family, social Capital in School and Expectation for educational achievement in children and adolescents. *Korean Soc. Sport Policy* 13, 1–12.

Kolinsky, R. (2015). How learning to read influences language and cognition. *The Oxford handbook of reading*. eds. A. Pollatsek and R. Treiman (New York, NY, US: Oxford University Press), 377–393.

Laube, C., Van Den Bos, W., and Fandakova, Y. (2020). The relationship between pubertal hormones and brain plasticity: implications for cognitive training in adolescence. *Dev. Cogn. Neurosci.* 42:100753. doi: 10.1016/j.dcn.2020.100753

Li, X., and Jiang, W. (2023). Impact of physical exercise and online gaming on adolescents' academic performance: an examination of the mediating effects of non-cognitive abilities. *J. Shandong Sport Univ.* 39, 80–90. doi: 10.14104/j.cnki.1006-2076.2023.04.010

Li, Z., Qin, W., and Patel, V. (2021). Associations of parental depression during adolescence with cognitive development in later life in China: a population-based cohort study. *PLoS Med.* 18:e1003464. doi: 10.1371/journal.pmed.1003464

Liu, M., Zhang, T., Tang, N., Zhou, F., and Tian, Y. (2022). The effect of educational expectations on Children's cognition and depression. *IJERPH* 19:14070. doi: 10.3390/ijerph192114070

Marmeleira, J. (2013). An examination of the mechanisms underlying the effects of physical activity on brain and cognition. *Eur. Rev. Aging Phys. Act.* 10, 83–94. doi: 10.1007/s11556-012-0105-5

Gilani, S. R. M., and Dashipour, A. (2016). The effects of physical activity on self-esteem: a comparative study. *Int J High Risk Behav Addict* 6:5955. doi: 10.5812/ijhrba.35955

Phillips, C. (2017). Brain-derived neurotrophic factor, depression, and physical activity: making the Neuroplastic connection. *Neural Plast.* 2017, 1–17. doi: 10.1155/2017/7260130

Qiong, W., and Peihua, L. (2016). Analysis of the reliability and validity of the mathematics test and vocabulary in the China family panel study. *China Examin* 11, 44–50. doi: 10.19360/j.cnki.11-3303/g4.2016.11.007

Reigal, R. E., Hernández-Mendo, A., Juárez-Ruiz de Mier, R., and Morales-Sánchez, V. (2020). Physical exercise and fitness level are related to cognitive and psychosocial functioning in adolescents. *Front. Psychol.* 11:11. doi: 10.3389/fpsyg.2020.01777

Ren, T., Yu, X., and Yang, W. (2019). Do cognitive and non-cognitive abilities mediate the relationship between air pollution exposure and mental health? *PLoS One* 14:e0223353. doi: 10.1371/journal.pone.0223353

Robinson, P. (2012). "Abilities to learn: cognitive abilities" in Encyclopedia of the sciences of learning. ed. N. M. Seel (New York: Springer), 17–20.

Ruiz-Hermosa, A., Mota, J., Díez-Fernández, A., Martínez-Vizcaíno, V., Redondo-Tébar, A., and Sánchez-López, M. (2020). Relationship between weight status and cognition in children: a mediation analysis of physical fitness components. *J. Sports Sci.* 38, 13–20. doi: 10.1080/02640414.2019.1676538

Shi, X., He, X., Pan, D., Qiao, H., and Li, J. (2022). Happiness, depression, physical activity and cognition among the middle and old-aged population in China: a conditional process analysis. *PeerJ* 10:e13673. doi: 10.7717/peerj.13673

Shigeta, T. T., Leahy, A. A., Smith, J. J., Eather, N., Lubans, D. R., and Hillman, C. H. (2021). Cardiorespiratory and muscular fitness associations with older adolescent cognitive control. *J. Sport Health Sci.* 10, 82–90. doi: 10.1016/j.jshs.2020.05.004

Sofi, F., Valecchi, D., Bacci, D., Abbate, R., Gensini, G. F., Casini, A., et al. (2011). Physical activity and risk of cognitive decline: a meta-analysis of prospective studies. *J. Intern. Med.* 269, 107–117. doi: 10.1111/j.1365-2796.2010.02281.x

Spear, L. P. (2013). Adolescent Neurodevelopment. *J. Adolesc. Health* 52, S7–S13. doi: 10.1016/j.jadohealth.2012.05.006

Tay, T. L., Savage, J. C., Hui, C. W., Bisht, K., and Tremblay, M.-È. (2017). Microglia across the lifespan: from origin to function in brain development, plasticity and cognition. *J. Physiol.* 595, 1929–1945. doi: 10.1113/JP272134

Teixeira, P. J., Silva, M. N., Mata, J., Palmeira, A. L., and Markland, D. (2012). Motivation, self-determination, and long-term weight control. *Int. J. Behav. Nutr. Phys. Act.* 9:22. doi: 10.1186/1479-5868-9-22

Vieira, I. S., Ferrugem, S. C. R., Reyes, A. N., Branco, J. C., Mondin, T. C., Cardoso, T. A., et al. (2021). Effects of depression and excess body weight on cognition and functioning in young adults: a population-based study. *J. Affect. Disord.* 282, 401–406. doi: 10.1016/j.jad.2020.12.083

Wang, S., Qin, J., and Li, D. (2024). Academic pressure or emotional detachment? The complex effect of compulsory boarding due to the school merger policy. *School Ment Health*, 1–15. doi: 10.1007/s12310-024-09698-y

Wilson, A. L., Nguyen, C., Bogomolova, S., Sharp, B., and Olds, T. (2019). Analysing how physical activity competes: a cross-disciplinary application of the duplication of behaviour law. *Int. J. Behav. Nutr. Phys. Act.* 16:123. doi: 10.1186/s12966-019-0847-9

Xie, Y., and Lu, P. (2015). The sampling design of the China family panel studies (CFPS). *Chin. J. Sociol.* 1, 471–484. doi: 10.1177/2057150X15614535

Zacharopoulos, G., Sella, F., and Cohen Kadosh, R. (2021). The impact of a lack of mathematical education on brain development and future attainment. *Proc. Natl. Acad. Sci.* 118:e2013155118. doi: 10.1073/pnas.2013155118

Zhang, Y. (2023). Can physical exercise reduce adolescents' deviant behaviors? Evidence from China education panel survey. *J. Educ. Stud.* 19, 171–185. doi: 10.14082/j.cnki.1673-1298.2023.04.016

Zhang, X., Chen, X., and Zhang, X. (2018). The impact of exposure to air pollution on cognitive performance. *Proc. Natl. Acad. Sci. USA* 115, 9193–9197. doi: 10.1073/pnas.1809474115

Zhong, H., Zhou, J., Xu, D., and Liu, T. (2022). Can school health education improve students' physical exercise time? Empirical research based on CEPS (2014–2015) survey data. *Front. Psychol.* 13:4275. doi: 10.3389/fpsyg.2022.1054275

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 09 April 2025
DOI 10.3389/fpsyg.2025.1387475

Check for updates

OPEN ACCESS

EDITED BY
Yaira Barranco-Ruiz,
University of Granada, Spain

REVIEWED BY
Pierluigi Diotaiuti,
University of Cassino, Italy
Soukaina Hattabi,
University of Jendouba, Tunisia

*CORRESPONDENCE
ShiLei Liu
✉ liushilei2007@126.com

RECEIVED 17 February 2024
ACCEPTED 26 March 2025
PUBLISHED 09 April 2025

CITATION
Xiang J, Guo K, Gao J, Gao Y and Liu S (2025) Exploring the mediating role of social support and learning engagement in the relationship between physical activity and academic achievement in secondary school students. *Front. Psychol.* 16:1387475. doi: 10.3389/fpsyg.2025.1387475

Exploring the mediating role of social support and learning engagement in the relationship between physical activity and academic achievement in secondary school students

Jun Xiang[1], Kelei Guo[1], Jia Gao[1], Yun Gao[2] and ShiLei Liu[3]*

[1]School of Physical Education and Health, Zhaoqing University, Zhaoqing, China, [2]Department of Physical Education, Shanghai Jiao Tong University, Shanghai, China, [3]School of Physical Education and Health, Wenzhou University, Wenzhou, China

Background: The academic achievement of secondary school students has consistently been a focal topic of interest among researchers. However, the relationship between physical activity and academic achievement, along with its underlying mechanisms, remains unclear. Therefore, the purpose of this study was to investigate the relationship between physical activity and academic achievement of secondary school students, and to verify the mediating role of social support and learning engagement between them.

Methods: Based on the purpose, a survey was conducted involving 3,230 secondary school students (*M* age = 13.21, *SD* age = 0.54) in Guangdong Province, utilizing the Physical Activity Level Scale, Academic Achievement Scale, Perceived Social Support Scale, and Learning Engagement Scale. Data were statistically analysed using descriptive statistics, correlation analysis, regression analysis and mediation analysis by using SPSS to examine the relationship between physical activity and academic achievement, as well as the mediating roles of social support and learning engagement.

Results: Independent Sample *t*-test were used to test gender differences, which were observed only in physical activity, with boys exhibiting significantly higher scores than girls (Boys: 36.41 ± 19.17; Girls: 34.21 ± 19.78; $p = 0.008$). ANOVA were used to test age differences, which were observed in physical activity ($F = 3.426$, $p = 0.001$) and learning engagement ($F = 3.054$, $p = 0.012$), with physical activity declining among middle school students as age increased, while learning engagement showed a continuous rise across all age stages. Regression analysis showed that the direct path from physical activity to academic achievement was significant ($\beta = -0.025$, $p < 0.01$). Physical activity positively predicted social support ($\beta = 0.085$, $p < 0.01$) and learning engagement ($\beta = 0.082$, $p < 0.01$). Social support significantly predicted learning engagement ($\beta = 0.096$, $p < 0.01$) and academic achievement ($\beta = -0.038$, $p < 0.01$). Social support and learning engagement play significant mediating roles in the relationship between physical activity and academic achievement, accounting for 90.25% of the total effect. The mediating effect consists of three pathways: (1) physical activity → social support → academic achievement (mediating effect is 0.017), (2) physical activity → learning engagement → academic achievement (mediating effect is 0.032), and (3) physical activity → social support → learning engagement → academic achievement (mediating effect is 0.062).

Conclusion: Physical activity not only directly predicts academic achievement in middle school students, but also directly through the separate mediating roles of social support and learning engagement, and indirectly through the chained mediating roles of social support and learning engagement. These findings underscore the significant influence of physical activity on academic achievement, offering valuable insights for educators in developing and implementing strategies that foster students' academic development.

KEYWORDS

physical activity, academic achievement, social support, learning engagement, mediation, secondary school students

Introduction

In July 2021, the General Office of the Central Committee of the Communist Party of China issued the "Opinions on Further Reducing the Burden of Homework and Extracurricular Training for Students in Compulsory Education." This document advocated for the effective use of students' leisure time, encouraging schools and parents to guide students in engaging in manageable household chores and appropriate physical exercise after school (Zhang et al., 2023). With increasing societal competition and ongoing educational reforms, stakeholders—including schools, parents, and students—continue to prioritize academic performance due to the influence of traditional examination-oriented education. This often results in a substantial investment of time and energy in cultural subjects, leading to a neglect of the importance of physical activity (Zhao et al., 2024). Over time, this has manifested in the frequent reallocation of physical education class hours to cultural subjects, resulting in students lacking sufficient opportunities for physical activity (Wang et al., 2023).

However, studies have shown that physical activity not only imparts motor skills and enhances students' physical fitness but also contributes to improved cognitive processing and executive functions, thereby enhancing students' mathematical performance (Ericsson and Karlsson, 2014). Longitudinal studies have further demonstrated that students who maintain good or improved levels of aerobic endurance tend to achieve higher scores on various academic assessments (Sardinha et al., 2016; Andersen et al., 2016). Moreover, engaging in physical exercise promotes students' physical health and facilitates the release of various neurotransmitters in the brain, which not only induces feelings of pleasure and enhances cognitive flexibility but also increases arousal levels and cognitive resources. This, in turn, fosters the development of a positive self-concept among students, thereby improving their psychological well-being and academic success (Jiang et al., 2016).

Given that middle school students face increasing academic pressures, physical activity may serve as an effective intervention to promote academic achievement (Gao et al., 2024). Few empirical studies have investigated the mechanisms underlying the relationship between physical activity and academic achievement. Therefore, this study aims to investigate the mechanisms through which physical activity influences academic achievement among secondary school students, while also analyzing the mediating roles of social support and learning engagement between the two variables. This research seeks to provide both theoretical and empirical evidence to enhance academic performance and foster academic engagement among secondary school students.

Literature view and research hypothesis

Physical activity and academic achievement

Recent studies highlight physical activity as a crucial factor influencing adolescents' overall well-being (Sun et al., 2021), demonstrating positive effects on both their physical and mental health (Pascoe et al., 2020). Specifically, higher levels of physical activity are linked to improved academic achievement, with active students often exhibiting greater motivation, self-discipline, and focus in their studies (Estrada-Tenorio et al., 2020). Engaging in moderate-intensity activities, such as jogging or swimming, has been shown to significantly enhance math and language scores (Singh et al., 2012). Additionally, physical activity reduces stress and anxiety, enhancing students' emotional states and focus during study sessions (Erdoğan Yüce and Muz, 2020). Therefore, the current study proposed Hypothesis 1: physical activity is positively associated with academic achievement in secondary school students.

The mediating role of social support

One of the mediating mechanisms in this study is the role of social support. Social support refers to support and encouragement from social relationships such as family members, teachers, and peers (Gottlieb and Bergen, 2010). First, social support plays an important role in an individual's academic achievement (Li et al., 2018). Social support from family, peers, and teachers can enhance students' motivation, self-confidence, and satisfaction with learning, thereby improving their academic performance (Toor, 2018). Fredricks and Eccles (2006) found that social support can increase students' motivation, which in turn promotes academic achievement. Second, engaging in physical activities, whether in team sports, group fitness classes, or recreational activities, brings people together with a common interest. These shared experiences facilitate interactions, which can lead to the formation of friendships and social networks (Fan et al., 2011). Therefore, the current study proposed Hypothesis 2: social support has a mediating role between physical activity and academic achievement of secondary school students.

Mediating role of learning engagement

The second mechanism of mediation in this study is the mediating role of learning engagement. Learning engagement refers to students' attention, commitment, and motivation to the learning task (Jang, 2008). A growing body of research indicates that physical activity exerts a positive influence on students' attitudes, attention, and motivation toward learning, which subsequently enhances their engagement and academic performance. For instance, de Bruijn et al. (2023) demonstrated that physical activity fosters students' attention and commitment to learning tasks, which in turn contributes to improved academic achievement. Similarly, Hagger et al. (2002) and Wiltshire et al. (2019) reported that students who engage in physical activity are more motivated and actively involved in their studies, yielding positive academic outcomes. Therefore, the current study proposed Hypothesis 3: learning engagement mediates between physical activity and academic achievement of secondary school students.

Chain mediating role of social support and learning engagement

Social support and learning engagement may have a chain mediating role between physical activity and academic achievement. Social support can increase students' self-esteem and self-confidence, which in turn increases their commitment and effort to academic tasks, social support can affect academic achievement by influencing learning engagement (Pfeifer et al., 2023). Therefore, the current study proposed Hypothesis 4: social support and learning engagement serve as chain mediating roles between physical activity and academic achievement of secondary school students.

In summary, scholars have pointed out the positive association between physical activity and academic achievement and emphasized the mediating and chain mediating roles of social support and learning engagement in this relationship, and the above findings provide a theoretical basis for the hypotheses of this study. Therefore, the research frame diagram were established (Figure 1): (1) to test the predictive role of physical activity on secondary school students' academic achievement; (2) to examine the mediating role of social support between physical activity and secondary school students' academic achievement; (3) to examine the mediating role of learning engagement between physical activity and secondary school students' academic achievement; (4) to test the chain-mediating roles of social support and learning engagement in the relationship between physical activity and secondary school students' academic achievement. Chain mediating role.

Method

Participant

To enhance the representativeness of the sample, factors such as economic status were taken into consideration. Based on the current administrative division of Guangdong Province, two secondary schools (42 in total) were randomly selected from each of the 21 prefecture-level cities in Guangdong Province, including Guangzhou, Shenzhen, Zhuhai, Shantou, and Foshan, as the sample sampling schools for this study. Two classes (Approximately 40–42 students are selected from each class) were randomly selected from each school (a total of 84 classes) and 3,528 questionnaires were distributed. The subjects were tested in the physical education classroom and the primary testers were professionally trained physical education teachers and psychology students. The tests were approved by the school director, classroom teachers and subjects, and all questionnaires were completed within 10 min. A group-based administration method was employed, with standardized instructions provided to guide participants in completing the questionnaires. After the questionnaires were recovered, they were excluded according to the following criteria: (1) missing data (e.g., participants did not complete the majority of the items); (2) inconsistent responses (e.g., participants provide answers that are logically contradictory); (3) absence of participation in physical exercise or limitations in physical activity; and (4) refusal by participants or their legal guardians to consent to participation. After collation 3,230 valid questionnaires were recovered for this study with a recovery rate of 92%. The age range of the participants was 12 to 17 years (*M* age = 13.21, *SD* age = 0.54), of which 1,578 were boys and 1712 were girls. The sample size was computed *a priori* by G∗Power 3.1 (Faul et al., 2007), using the power of (1-β) = 0.95, medium effect size$|\rho|$ = 0.3 of the expected variable-correlations and a two-tail test. The recommended sample size by G∗Power calculation was 134 and we obtain reliable statistical calculations. In addition, the study was supported and approved by the Institutional Review Board of Zhaoqing University. All secondary school and the student's families signed an informed consent form. The informed consent form described the purpose and process of the study, the methodology used, and also included information on the assurance of confidentiality, the principle of voluntary participation, and the contact information of the researchers. The variables such as gender and class of the subjects were also controlled.

Research methods

Psychometric methods

Physical activity rating scale

The Physical Activity Rating Scale (PARS-3) compiled by Liang (1994) was chosen, which is widely used within the field of physical activity, and it is mainly used to assess an individual's level of physical activity. The PARS-3 is a self-reported scale and consists of three dimensions: intensity of activity (e.g., How would you describe the intensity of your physical exercise?), duration of activity (e.g., How much time do you spend on exercise each time?), and number of activities (e.g., How many times do you participate in this exercise activity?). Each item is divided into five levels and scored 1–5 points. Physical activity exercise = intensity × time × frequency, and the amount of physical activity is converted to a maximum of 100 points and a minimum of 0. The criteria for the development of the Physical

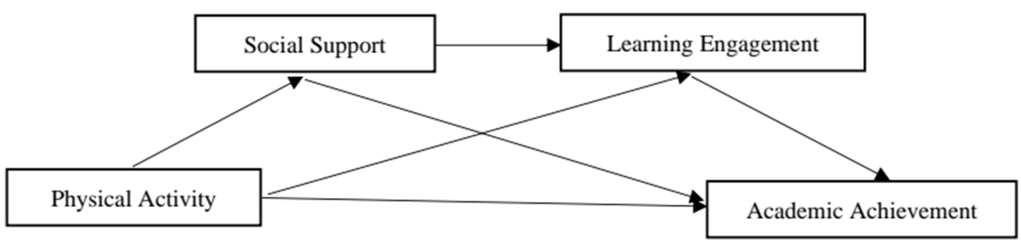


FIGURE 1
Research frame diagram.

10.3389/fpsyg.2025.1387475

Activity Scale are as follows: low activity ≤ 19 points; slightly low activity ≤ 20–39 points; moderate activity ≤ 40–59 points; slightly high activity ≤ 60–79 points; high activity ≤ 80–100 points. Previous study proved that the scale has good reliability and validity in the middle school student population (Yan et al., 2020). In this study, the Cronbach's α coefficient of the scale is 0.51, which indicates that the scale questionnaire has acceptable reliability and validity, although it is lower than the value reported in Yan's study (α = 0.76; Yan et al., 2020).

Academic achievement scale

The Academic Achievement Questionnaire developed by Wen et al. (2010) was used to ask students to evaluate their academic achievement in 3 subjects, namely, language, mathematics and English. The response options incorporated a 5-point Likert scale, which ranged from 1 (very bad) to 5 (very good), and the average score of the three subjects was finally calculated. In addition, considering the combined calculation of the test scores of the two subjects, this study did a score conversion of the raw test scores during data processing (mean 50, standard deviation 10), and the higher the score, the stronger the academic achievement of the subjects (Zhu, 2014). Previous study proved that the scale has good reliability and validity in the secondary school student population (Lin, 2021). In this study, the Cronbach's α coefficient of the scale is 0.88, similar to Lin's study (α = 0.72), which indicates that the scale questionnaire has good reliability and validity.

Social support scale

The Perceived Social Support Scale was originally developed by Zimet et al., 1988 and later translated and revised by Jiang (2009). The scale consists of 12 questions in 3 dimensions (family support, friend support, and other support). The response options incorporated a 5-point Likert scale, which ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). Higher total scores indicating higher levels of social support. Research has proved that the scale has good reliability and validity in the secondary school student population (Xu, 2023). In this study, the Cronbach's alpha coefficient of the scale is 0.879, similar to Xu's study (α = 0.89), which indicates that the scale questionnaire in this study has good reliability and validity.

Learning engagement scale

The Learning Engagement Scale developed by Schaufeli et al. (2002) revised by Fang et al. (2008) was used. The revised scale consists of three dimensions: vigor (6 items), dedication (5 items), and concentration (6 items), with a total of 17 items. The response options incorporated a 7-point Likert scale, which ranged from 1 (never) to 5 (always). Higher total scores indicating higher levels of learning engagement. Research has proved that the scale has good reliability and validity (Gong, 2022). In this study, the Cronbach's alpha coefficient of the scale is 0.92, similar to Gong's study (α = 0.97), which indicates that the scale questionnaire in this study has good reliability and validity.

Data collecting procedure

First, 1 week prior to the formal signing of the informed consent forms by the middle school students, the research team distributed guardian versions of the informed consent forms to 3,528 students across 84 selected classes. The consent forms informed guardians about the purpose, significance, and content of the study (students were instructed to explain the contents of the consent forms to their parents and to inform them that they needed to sign). Additionally, students from the selected classes were required to bring the guardian versions of the consent forms back to school on the day of the formal testing and submit them to the testing staff. Second, on the day of the formal testing, middle school students were given ample time and opportunity to review the details of the test before signing the informed consent form. Researchers thoroughly answered any questions related to the study posed by the participants. Due to factors such as the large number of students selected from classes, the need for guardians to sign the consent forms before testing, and the varying schedules for physical education classes, the testing process ultimately collected participants' basic information (age, gender, etc.), as well as their evaluations of physical activity, academic achievement, social support, and learning engagement. The entire process took a month to complete.

Mathematical and statistical method

After the questionnaire of this study was recovered and screened again to exclude invalid data, the data of this study were statistically analyzed using SPSS21.0 and SPSS macro program prepared by Hayes. The SPSS PROCESS macro is a widely used tool for mediation and moderation analysis, allowing for a clear examination of complex relationships among variables (Hayes and Aut, 2018). Previous studies have used this method to analyze mediating effects (e.g., Liu et al., 2024). First, descriptive statistics with test of difference were performed on the test data of demographic information, physical activity, academic achievement, social support, and commitment to learning using SPSS 21.0 software. Second, common method bias was tested using public latent factors in SPSS 21.0 software. Third, Pearson's bivariate relationship between physical activity, academic achievement, social support and learning engagement among secondary school students was tested using SPSS 21.0. Fourth, PROCESS model 6 and Bootstrap (5,000 times) sampling technique were utilized to test the mediating roles of social support and learning engagement, and the chain mediating role between physical activity and academic achievement after control gender and age. In this study, $p < 0.05$ was set as statistical result and significant.

Research results

Common method bias test

Data collection using questionnaires may be at risk of common method bias. Therefore, before analyzing the data, Harman's one-factor test was used for statistical control, i.e., the items of all variables were subjected to unrotated principal component factor analysis (Zhou and Long, 2004). The results showed that there were six factors with eigenvalues greater than 1 extracted from the results of the unrotated exploratory factor analysis, and the variance of variance explained by the first factor was 29.80%, which was less than the critical value of 40% (Yan et al., 2020). It means that there is no factor that can explain most of the variance in this study, so the data in this study does not have serious common method bias and meets the conditions for further chained mediation effect test.

Descriptive statistics of physical activity, academic achievement, social support and learning engagement

The statistical results in Table 1 show that physical activity, academic achievement, social support, and learning engagement are not statistically significant when analyzed by gender differences ($p > 0.05$); physical activity, academic achievement, and learning engagement are statistically significant when analyzed by age differences ($p < 0.05$), and social support is not statistically significant when analyzed by age differences ($p > 0.05$). Boys scored slightly higher than girls in the physical activity and social support tests, while they scored slightly lower than girls in the academic achievement and learning engagement tests. In terms of physical activity, the amount of exercise among middle school students tends to decline with age. In contrast, regarding learning engagement, there is a continuous increase in engagement across all age stages as age increases. In terms of academic achievement and social support, there are no significant changes in academic performance across different age stages (see Table 2).

Correlation analysis of physical activity, academic achievement, social support and learning engagement

As can be seen from Table 3, physical activity showed significant positive correlations with academic achievement, social support, and learning engagement. Additionally, academic achievement was positively correlated with both social support and learning engagement, and a significant correlation was found between social support and learning engagement.

Testing the mediating effects of social support and learning engagement

Physical activity was taken as the independent variable, social support and learning involvement as the mediating variable, and academic achievement as the dependent variable. The SPSS macro model 6 was adopted (Hayes and Aut, 2018), and non-parametric percentile Bootstrap test with deviation correction was selected (repeated sampling 5,000 times). A 95% confidence interval was calculated to analyze the effects of the chain mediation model (Wen et al., 2022). After control gender and age, the results showed that physical activity positively associated with academic achievement, $\beta = 0.021$, $p < 0.01$, supporting Hypothesis 1. Physical activity was positively associated with social support, $\beta = 0.013$, $p < 0.01$. Social support was positively associated with academic achievement, $\beta = 0.043$, $p < 0.01$, supporting Hypothesis 2. Physical activity was positively associated with learning engagement, $\beta = 0.52$, $p < 0.01$. Learning engagement was positively associated with academic achievement, $\beta = 0.095$, $p < 0.01$, supporting Hypothesis 3. Social support was positively associated with learning engagement $\beta = 0.073$, $p < 0.01$, supporting Hypothesis 4 (see Table 4).

The results of the mediation effect test are shown in Table 5, Bootstrap 95% confidence interval of the indirect effects of physical activity on academic achievement does not include 0. These findings further support Hypotheses 2 to 4 (Figure 2).

Discussion

As predicted, the current study found that (1) physical activity positively associated with academic achievement; (2) Social support and learning engagement mediated the relationship between physical activity and academic achievement.

Physical activity and academic achievement

The results of this study show that there is a positive relationship between physical activity and academic achievement, which is consistent with numerous earlier studies (Sallis et al., 2012; Coe et al., 2006). First, engaging in physical activities enhances cognitive function and attention, leading to improved learning capabilities (Sallis et al., 2012). Moreover, physical activity contributes to the enhancement of working memory and the speed of information processing, which are positively correlated with academic achievement (Jiang et al., 2016). Secondly, physical activity promotes physical health and psychological well-being, enhancing students' motivation and learning effectiveness. Regular participation in physical activities helps students maintain good health, increases fitness levels, and boosts endurance, resulting in greater energy and concentration in their studies (Coe et al., 2006).

TABLE 1 Gender differences in physical activity, academic achievement, social support, and learning engagement.

Variable	Gender	Number (%)	*M*	SD	*t*	*p*
Physical activity	Male	1,518 (47%)	36.41	19.17	2.523	0.008
	Female	1,712 (53%)	34.21	19.78		
Social support	Male	1,518 (47%)	52.13	11.32	1.378	0.375
	Female	1,712 (53%)	51.93	11.36		
Learning engagement	Male	1,518 (47%)	67.39	16.71	0.969	0.613
	Female	1,712 (53%)	66.19	16.12		
Academic achievement	Male	1,518 (47%)	53.67	1.00	0.582	0.841
	Female	1,712 (53%)	53.67	0.97		

10.3389/fpsyg.2025.1387475

TABLE 2 Age difference of physical activity, academic achievement, social support and learning engagement test results.

Variable	Age	Number (%)	*M*	SD	*F*	*p*
Physical activity	12	485 (15.02%)	42.28	18.59	3.426	0.001
	13	1,130 (34.98%)	39.98	18.86		
	14	452 (13.99%)	38.74	16.51		
	15	388 (12.01%)	39.55	17.24		
	16	419 (12.97%)	22.51	4.63		
	17	356 (11.02%)	20.33	4.78		
Social support	12	485 (15.02%)	49.96	11.67	2.109	0.061
	13	1,130 (34.98%)	52.14	11.34		
	14	452 (13.99%)	51.89	11.35		
	15	388 (12.01%)	54.23	6.11		
	16	419 (12.97%)	54.61	4.35		
	17	356 (11.02%)	42.67	15.61		
Learning engagement	12	485 (15.02%)	62.79	14.39	3.054	0.012
	13	1,130 (34.98%)	66.77	16.35		
	14	452 (13.99%)	67.82	16.62		
	15	388 (12.01%)	68.44	21.82		
	16	419 (12.97%)	70.39	14.86		
	17	356 (11.02%)	73.78	17.34		
Academic achievement	12	485 (15.02%)	53.96	0.76	2.157	0.057
	13	1,130 (34.98%)	53.65	0.98		
	14	452 (13.99%)	53.68	1.12		
	15	388 (12.01%)	53.29	1.33		
	16	419 (12.97%)	53.89	0.84		
	17	356 (11.02%)	53.89	1.32		

TABLE 3 Correlation analysis and statistics of physical activity, academic achievement, social support and learning engagement.

Variable	$M \pm SD$	Physical activity	Academic achievement	Social support	Learning engagement
Physical activity	36.04 ± 19.49	1			
Academic achievement	53.67 ± 0.99	0.37**	1		
Social support	52.03 ± 11.34	0.58**	0.55**	1	
Learning engagement	67.13 ± 16.40	0.43**	0.89**	0.66**	1

$N = 3,230$. ** $p < 0.01$.

Furthermore, the results of this study indicate that there are gender differences in physical activity among middle school students. Boys scored slightly higher than girls in physical activity. A possible explanation is that boys are often encouraged to participate in more vigorous physical activities and sports, resulting in higher activity levels (Ridgers et al., 2006). Culturally, there may be stereotypes that associate physicality and competitiveness with masculinity, motivating boys to participate more in sports and physical activities (Telford et al., 2016).

Mediating role of social support

The results of this study show that social support plays a mediating role between physical activity and academic achievement, which indicated that physical activity is positively associated with social support, thereby increasing students' academic achievement. This is consistent with the findings of Fredricks and Eccles (2006) and Hagger et al. (2002). Social support can enhance students' motivation and opportunities to engage in physical activity by providing encouragement and assistance, thereby facilitating improvements in academic achievement. Researchers have found that the perception of family support can enhance students' levels of physical activity, and increased physical activity is positively correlated with students' academic performance. Therefore, it is believed that family support can improve academic achievement by promoting students' physical activity (Barbosa et al., 2020). Scholars have also discovered a significant positive relationship between teacher support and students' physical activity levels and academic

TABLE 4 Regression analysis of the chain mediation model between physical activity and academic achievement.

Variable	Social support		Learning engagement		Academic achievement	
	β	*t*	β	*t*	β	*t*
Gender	0.032	6.26**	0.047	7.81**	0.004	0.914
Age	0.021	6.221**	0.043	7.626**	0.051	8.013**
Physical activity	0.033	6.331**	0.072	11.013**	0.059	8.422**
Social support			0.083	12.086**	0.063	9.573**
Learning engagement					0.095	13.192**
R^2	1.921		1.473		1.814	
F	123.242		143.941		253.883	

*$P < 0.05$, **$P < 0.01$.

TABLE 5 Tests the mediating effects of social support and learning engagement on physical activity and academic achievement.

Effect type	Effect size	Boot SE	Bootstrap95% CI		Effect ratio
			Floor	Upper limit	
Total effect	0.123	0.089	0.029	0.052	100%
Direct effect	0.012	0.039	0.015	0.036	9.76%
Physical activity - Social support - Academic achievement	0.017	0.090	0.035	0.070	13.82%
Physical activity - Learning engagement - Academic achievement	0.032	0.053	0.015	0.075	26.02%
Physical activity - Social support - Learning engagement - Academic achievement	0.062	0.077	0.012	0.021	50.41%
Total indirect effect	0.111	0.078	0.011	0.023	90.24%

achievement, as teacher support can stimulate students' interest in engaging in physical activities and provide relevant opportunities and guidance (Vella et al., 2015). Additionally, research has shown that perceived peer support is significantly positively associated with students' physical activity levels and academic achievement. Social support comes not only from family and school environments but also from social networks and communities. Friends and peers in students' social networks can influence their physical activity and academic success (Anderson et al., 2006). Therefore, in the process of improving students' academic achievement, it is essential to emphasize social support, providing students with ample encouragement and support.

Mediating role of learning engagement

The results of this study show that learning engagement plays a mediating role between physical activity and academic achievement, which means that learning engagement can indirectly contribute to students' academic achievement by influencing their participation in physical activity. These findings align with previous studies examining mediating factors in academic performance (Diotaiuti et al., 2021), which emphasized the role of emotional balance and procrastination in shaping students' outcomes. Studies show that students who engage in physical activities exhibit higher levels of learning motivation, learning goals, and the use of learning strategies. Physical activity can enhance students' autonomy and self-regulation skills, thereby promoting their learning engagement (Nurmi et al., 2016). Additionally, physical activity can facilitate students' flow experiences, characterized by concentration and immersion in the context (Beauchamp and Morton, 2011). Furthermore, research has found that learning engagement significantly predicts academic achievement (Fredricks et al., 2004). Thus, learning engagement is considered a crucial bridge between physical activity and academic success. By promoting students' learning engagement, physical activities can positively impact their academic development.

Chain mediating role of social support and learning engagement

The results of this study indicate that social support and learning engagement play an important chain-mediated role between physical activity and academic achievement. This is consistent with previous research findings (Hillman et al., 2008). Social support can provide learning resources and guidance, which in turn affects students' levels of learning engagement. Support from family, peers, and teachers not only offers learning resources and information but also provides guidance and assistance (Leo et al., 2022). Social support can create opportunities for resource and information sharing, enhancing students' motivation and academic achievement (Wu et al., 2023; Meece et al., 2006). When students encounter learning difficulties or setbacks, receiving support and encouragement from others helps them adjust their learning attitudes and boost their motivation, leading to more active participation in learning activities.

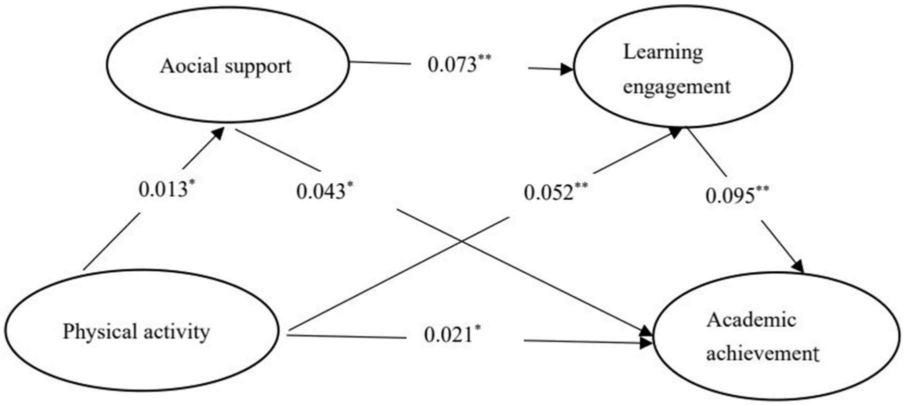


FIGURE 2
The chain mediation model of social support and learning engagement between physical activity and academic achievement.

Practical implications

The results of this study highlight the importance of promoting physical activity as a key element in enhancing academic achievement among secondary school students. Given the chain-mediating role of social support and learning engagement, educators and policymakers should consider adopting a more holistic approach to student development. Schools should integrate structured physical activity programs into the daily schedule, such as offering more diverse physical education classes and encouraging extracurricular sports activities. In parallel, schools should work to build supportive environments by strengthening peer relationships, fostering positive teacher-student connections, and creating systems that promote social support among students. This could include mentorship programs, team-based projects, or peer support networks.

Furthermore, by recognizing the positive impact of learning engagement, educators can develop strategies to make academic tasks more interactive and engaging. Policymakers can also allocate resources toward training teachers to create active learning environments and provide more personalized feedback, which could further enhance students' involvement in their learning process.

Limitation and suggestions for future study

This study provides a theoretical contribution to the study of academic achievement of secondary school students, the role of physical activity in intervening in the academic achievement of secondary school students as well as in increasing social support and facilitating learning engagement. However, it also has the following shortcomings:

1. Sample limitation: The sample is limited to one region (Guangdong), so the findings may not be generalizable to other areas. Future research could consider expanding the sample size to include students from more regions and diverse backgrounds to enhance the external validity of the findings.
2. Self-reported data: The measurements rely on questionnaires, which may introduce biases due to students' self-perception. To improve the objectivity and reliability of the findings, future research could incorporate objective measurement indicators, such as physical activity monitors and academic performance records, to obtain more accurate data.
3. Possible interfering variables: Factors such as socioeconomic status, study hours, or quality of instruction were not controlled. Future research could control for these potential confounding factors to obtain more accurate results.
4. Long-term effects: This study primarily focused on the relationship between physical activity and middle school students' academic achievement but did not consider long-term effects. Future research could conduct longitudinal studies to understand the long-term impact of physical activity on academic achievement and determine whether the mediating roles of social support and learning engagement remain stable at different time points.

Conclusion

This study explores the relationship between physical activity and academic achievement among middle school students, verifying the mediating roles of social support and learning engagement between the relationship between these two variables. First, there are gender and age differences in physical activity among middle school students. Second, here is a significant positive relationship between physical activity and academic achievement in middle school students, indicating that physical activity has a positive impact on their academic achievement. Third, physical activity not only directly predicts academic achievement but also indirectly predicts it through the chain mediating effects of social support and learning engagement. Based on these findings, schools and educational institutions should implement measures to promote student participation in physical activities, enhance social support, and foster a positive learning environment to improve academic development.

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 humans were approved by review Committee of the Academic Committee of the School of Physical Education and Health, Zhaoqing University. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

JX: Writing – original draft, Writing – review & editing. KG: Conceptualization, Investigation, Writing – review & editing. JG: Data curation, Writing – review & editing, Investigation. YG: Writing – review & editing. SL: Conceptualization, Data curation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was supported by the following projects: The 2023 Guangdong Education Science Planning Project (2023GXJK528); The 2023 Project of the 14th Five-Year Plan of the Guangdong Higher Education Association (23GQN24); Research Project of Provincial Primary and Secondary School Teacher Development Centre of Zhaoqing University (ZQXYJSFZZX202305); 2023 Zhaoqing Science and Technology Innovation Guidance Category (2023040317011); Key Projects of the University Research Fund of Zhaoqing University 2024 (ZD202401).

Acknowledgments

We would like to thank all participants who helped us complete this study.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Andersen, M. P., Mortensen, R. N., Vardinghus-Nielsen, H., Franch, J., Torp-Pedersen, C., and Bøggild, H. (2016). Association between physical fitness and academic achievement in a cohort of Danish school pupils. *J. Sch. Health* 86, 686–695. doi: 10.1111/josh.12422

Anderson, E. S., Wojcik, J. R., Winett, R. A., and Williams, D. M. (2006). Social-cognitive determinants of physical activity: the influence of social support, self-efficacy, outcome expectations, and self-regulation among participants in a church-based health promotion study. *Health Psychol.* 25, 510–520. doi: 10.1037/0278-6133.25.4.510

Barbosa, A., Whiting, S., Simmonds, P., Scotini Moreno, R., Mendes, R., and Breda, J. (2020). Physical activity and academic achievement: an umbrella review. *Int. J. Environ. Res. Public Health* 17:5972. doi: 10.3390/ijerph17165972

Beauchamp, M. R., and Morton, K. L. (2011). Transformational teaching and physical activity engagement among adolescents. *Exerc. Sport Sci. Rev.* 39, 133–139. doi: 10.1097/JES.0b013e31822153e7

Coe, D. P., Pivarnik, J. M., Womack, C. J., Reeves, M. J., and Malina, R. M. (2006). Effect of physical education and activity levels on academic achievement in children. *Med. Sci. Sports Exerc.* 38, 1515–1519. doi: 10.1249/01.mss.0000227537.13175.1b

de Bruijn, A. G., de Greeff, J. W., Temlali, T. Y., Oosterlaan, J., Smith, J., and Hartman, E. (2023). Objectively measured physical activity during primary school physical education predicts intrinsic motivation independently of academic achievement level. *Br. J. Educ. Psychol.* 93, 90–112. doi: 10.1111/bjep.12527

Diotaiuti, P., Valente, G., Mancone, S., and Bellizzi, F. (2021). A mediating model of emotional balance and procrastination on academic performance. *Front. Psychol.* 12:665196. doi: 10.3389/fpsyg.2021.665196

Erdoğan Yüce, G., and Muz, G. (2020). Effect of yoga-based physical activity on perceived stress, anxiety, and quality of life in young adults. *Perspect. Psychiatr. Care* 56, 697–704. doi: 10.1111/ppc.12484

Ericsson, I., and Karlsson, M. K. (2014). Motor skills and school performance in children with daily physical education in school a 9-year intervention study. *Scand. J. Med. Sci. Sports* 24, 273–278. doi: 10.1111/j.1600-0838.2012.01458.x

Estrada-Tenorio, S., Julián, J. A., Aibar, A., Martín-Albo, J., and Zaragoza, J. (2020). Academic achievement and physical activity: the ideal relationship to promote a healthier lifestyle in adolescents. *J. Phys. Act. Health* 17, 525–532. doi: 10.1123/jpah.2019-0320

Fan, Y., Das, K. V., and Chen, Q. (2011). Neighborhood green, social support, physical activity, and stress: assessing the cumulative impact. *Health Place* 17, 1202–1211. doi: 10.1016/j.healthplace.2011.08.008

Fang, L., Shi, K., and Zhang, F. (2008). A reliability study of the Chinese version of the learning engagement scale. *Chin. J. Clin. Psych.* 6, 618–620.

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G* power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39, 175–191. doi: 10.3758/BF03193146

Fredricks, J. A., Blumenfeld, P. C., and Paris, A. H. (2004). School engagement: potential of the concept, state of the evidence. *Rev. Educ. Res.* 74, 59–109. doi: 10.3102/00346543074001059

Fredricks, J. A., and Eccles, J. S. (2006). Is extracurricular participation associated with beneficial outcomes? Concurrent and longitudinal relations. *Dev. Psychol.* 42, 698–713. doi: 10.1037/0012-1649.42.4.698

Gao, Y., Yu, Q., Schuch, F. B., Herold, F., Hossain, M. M., Ludyga, S., et al. (2024). Meeting 24-h movement behavior guidelines is linked to academic engagement, psychological functioning, and cognitive difficulties in youth with internalizing problems. *J. Affect. Disord.* 349, 176–186. doi: 10.1016/j.jad.2024.01.017

Gong, X. (2022). The effect of future time insight on secondary school students' learning engagement: A moderated mediation model. (Master's thesis, Suzhou University of Science and Technology). doi: 10.27748/d.cnki.gszkj.2022.000436

Gottlieb, B. H., and Bergen, A. E. (2010). Social support concepts and measures. *J. Psychosom. Res.* 69, 511–520. doi: 10.1016/j.jpsychores.2009.10.001

Hagger, M. S., Chatzisarantis, N. L., and Biddle, S. J. (2002). A meta-analytic review of the theories of reasoned action and planned behavior in physical activity: predictive validity and the contribution of additional variables. *J. Sport Exerc. Psychol.* 24, 3–32. doi: 10.1123/jsep.24.1.3

Hayes, A. F., and Aut, V. X. X. (2018). Introduction to mediation, moderation, and conditional process analysis a regression-based approach. AF Hayes; series Editor's note by T.D. Little.

Hillman, C. H., Erickson, K. I., and Kramer, A. F. (2008). Be smart, exercise your heart: exercise effects on brain and cognition. *Nat. Rev. Neurosci.* 9, 58–65. doi: 10.1038/nrn2298

Jang, H. (2008). Supporting students' motivation, engagement, and learning during an uninteresting activity. *J. Educ. Psychol.* 100, 798–811. doi: 10.1037/a0012841

Jiang, Q. (2009). Comprehending the social support scale. *Chin. J. Ment. Health* 29, 131–133.

Jiang, Y., Yang, Y., and Xing, S. (2016). A review of the progress of research on the promotion of children's academic achievement by physical education and its mechanism of action. *J. Phys. Educ.* 5, 86–92. doi: 10.16237/j.cnki.cn44-1404/g8.20160721.002

Leo, F. M., Mouratidis, A., Pulido, J. J., López-Gajardo, M. A., and Sánchez-Oliva, D. (2022). Perceived teachers' behavior and students' engagement in physical education: the mediating role of basic psychological needs and self-determined motivation. *Phys. Educ. Sport Pedagog.* 27, 59–76. doi: 10.1080/17408989.2020.1850667

Li, J., Han, X., Wang, W., Sun, G., and Cheng, Z. (2018). How social support influences university students' academic achievement and emotional exhaustion: the mediating role of self-esteem. *Learn. Individ. Differ.* 61, 120–126. doi: 10.1016/j.lindif.2017.11.016

Liang, D. (1994). Stress levels of college students and their relationship with physical activity. *Chin. J. Ment. Health* 1, 5–6.

Lin, S. (2021). The effects of stressful life events on secondary school Students' academic achievement. (Master's Degree Thesis, Fujian Normal University). doi: 10.27019/d.cnki.gfjsu.2021.001387

Liu, D., Geng, X., Zhang, F., Zhang, Y., and Li, X. (2024). The influence of negative life events on college students' suicidal ideation: the mediating role of entity theory and the moderating role of meaning in life. *Front. Psychol.* 15:1443474. doi: 10.3389/fpsyg.2024.1443474

Meece, J. L., Anderman, E. M., and Anderman, L. H. (2006). Classroom goal structure, student motivation, and academic achievement. *Annu. Rev. Psychol.* 57, 487–503. doi: 10.1146/annurev.psych.56.091103.070258

Nurmi, J., Hagger, M. S., Haukkala, A., Araújo-Soares, V., and Hankonen, N. (2016). Relations between autonomous motivation and leisure-time physical activity participation: the mediating role of self-regulation techniques. *J. Sport Exerc. Psychol.* 38, 128–137. doi: 10.1123/jsep.2015-0222

Pascoe, M., Bailey, A. P., Craike, M., Carter, T., Patten, R., Stepto, N., et al. (2020). Physical activity and exercise in youth mental health promotion: a scoping review. *BMJ open sport—exercise. Medicine* 6:e000677. doi: 10.1136/bmjsem-2019-000677

Pfeifer, M. A., Cordero, J. J., and Stanton, J. D. (2023). What I wish my instructor knew: how active learning influences the classroom experiences and self-advocacy of STEM majors with ADHD and specific learning disabilities. *CBE—life sciences. Education* 22:ar2. doi: 10.1187/cbe.21-12-0329

Ridgers, N. D., Stratton, G., and Fairclough, S. J. (2006). Physical activity levels of children during school playtime. *Sports Med.* 36, 359–371. doi: 10.2165/00007256-200636040-00005

Sallis, J. F., Floyd, M. F., Rodríguez, D. A., and Saelens, B. E. (2012). Role of built environments in physical activity, obesity, and cardiovascular disease. *Circulation* 125, 729–737. doi: 10.1161/CIRCULATIONAHA.110.969022

Sardinha, L. B., Marques, A., Minderico, C., Palmeira, A., Martins, S., Santos, D., et al. (2016). Longitudinal relationship between cardiorespiratory fitness and academic achievement. *Med. Sci. Sports Exerc.* 48, 839–844. doi: 10.1249/MSS.0000000000000830

Schaufeli, W. B., Martinez, I. M., Pinto, A. M., Salanova, M., and Bakker, A. B. (2002). Burnout and engagement in university students: a cross-national study. *J. Cross-Cult. Psychol.* 33, 464–481. doi: 10.1177/0022022102033005003

Singh, A., Uijtdewilligen, L., Twisk, J. W., Van Mechelen, W., and Chinapaw, M. J. (2012). Physical activity and performance at school: a systematic review of the literature including a methodological quality assessment. *Arch. Pediatr. Adolesc. Med.* 166, 49–55. doi: 10.1001/archpediatrics.2011.716

Sun, Y., Liu, W., Xiong, L., Qu, Y., Chen, S., Wu, D., et al. (2021). Relationship between moderate to vigorous physical activity, screen time and depressive symptoms among middle school students in Guangzhou. *School Health China* 42, 1499–1503. doi: 10.16835/j.cnki.1000-9817.2021.10.013

Telford, R. M., Telford, R. D., Olive, L. S., Cochrane, T., and Davey, R. (2016). Why are girls less physically active than boys? Findings from the LOOK longitudinal study. *PLoS One* 11:e0150041. doi: 10.1371/journal.pone.0150041

Toor, K. K. (2018). Parent-child relationship and students' academic achievement: a study of secondary school students. *MIER J. Educ. Stud. Trends Pract.* 38-56, 38–56. doi: 10.52634/mier/2018/v8/i1/1418

Vella, S. A., Cliff, D. P., Magee, C. A., and Okely, A. D. (2015). Associations between sports participation and psychological difficulties during childhood: a two-year follow up. *J. Sci. Med. Sport* 18, 304–309. doi: 10.1016/j.jsams.2014.05.006

Wang, Y., Zhangm, Y., Zhu, Y., Lin, X., and Li, Y. (2023). The influence of physical education curriculum implementation on fourth grade mathematics academic achievement: based on the empirical research of National Compulsory Education Quality Assessment. *J. China Examinat.* 2, 64–72. doi: 10.19360/j.cnki.11-3303/g4.2023.02.009

Wen, Z., Fang, J., Xie, J., and Ouyang, J. (2022). Methodological research on mediation effects in China's mainland. *Adv. Psychol. Sci.* 30, 1692–1702. doi: 10.3724/SP.J.1042.2022.01692

Wen, C., Zhang, W., Li, D., Yu, C., and Dai, W. (2010). The relationship between gratitude and academic achievement in junior high school students: the mediating role of learning engagement. *Psychol. Dev. Educ.* 6, 598–605. doi: 10.16187/j.cnki.issn1001-4918.2010.06.013

Wiltshire, G., Lee, J., and Williams, O. (2019). Understanding the reproduction of health inequalities: physical activity, social class and Bourdieu's habitus. *Sport Educ. Soc.* 24, 226–240. doi: 10.1080/13573322.2017.1367657

Wu, J., Fu, H., and Zhang, Y. (2023). A meta-analysis of the relationship between perceived social support and students' academic achievement: the mediating role of learning engagement. *Adv. Psychol. Sci.* 31, 552–569. doi: 10.3724/SP.J.1042.2023.00552

Xu, M. (2023). The effects of middle school students' perceptions of social support, self-compassion, and empathy on the protective behaviours of bystanders of school bullying. Master's thesis, Minzu Normal University). doi: 10.27726/d.cnki.gzzsf.2023.000244

Yan, J., Tao, B., Shi, L., Lou, H., Li, H., and Liu, M. (2020). The relationship between adolescents' extracurricular physical activity and school adjustment: chain mediation model and gender differences. *Chin. Sports Sci. Technol.* 10, 11–18. doi: 10.16470/j.csst.2020161

Zhang, W., Xiao, S., and Fu, W. (2023). Can "smart homework" achieve the goal of Chinese "double reduction" policy to reduce burden and improve quality?—the positive and negative effects of "smart homework" on students. *Sustain. For.* 15:9759. doi: 10.3390/su15129759

Zhao, N., Shi, C., and Wang, C. (2024). Effects of the "double reduction" policy on the commercial tutoring sector in China. *Int. J. Educ. Dev.* 105:102989. doi: 10.1016/j.ijedudev.2024.102989

Zhou, H., and Long, L. (2004). Statistical remedies for common method biases. *Adv. Psychol. Sci.* 12:942.

Zhu, J. (2014). Research on the relationship between learning stress, motivation, self-confidence in learning and academic achievement of secondary school students. (Master's thesis, Central China Normal University).

Zimet, G. D., Dahlem, N. W., Zimet, S. G., and Farley, G. K. (1988). The multidimensional scale of perceived social support. *J. Pers. Assess.* 52, 30–41. doi: 10.1207/s15327752jpa5201_2

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 19 June 2025
DOI 10.3389/fpsyg.2025.1445144

Check for updates

OPEN ACCESS

EDITED BY
María Rodriguez-Ayllon,
Erasmus Medical Center, Netherlands

REVIEWED BY
Arkadiusz M. Jasiński,
University of Opole, Poland
Valentina Baldini,
University of Bologna, Italy

*CORRESPONDENCE
James W. Whitworth
✉ jwhitwor@bu.edu

RECEIVED 06 June 2024
ACCEPTED 23 May 2025
PUBLISHED 19 June 2025

CITATION
SantaBarbara NJ, Checko ER, Pebole MM and Whitworth JW (2025) Cross-sectional exercise-related differences in PTSD symptoms, psychological distress, physical pain, and sleep quality in trauma-exposed adults.
Front. Psychol. 16:1445144.
doi: 10.3389/fpsyg.2025.1445144

Cross-sectional exercise-related differences in PTSD symptoms, psychological distress, physical pain, and sleep quality in trauma-exposed adults

Nicholas J. SantaBarbara[1,2], Erica R. Checko[3,4], Michelle M. Pebole[5] and James W. Whitworth[2,3,4,5]*

[1]School of Nursing and Health Sciences, Merrimack College, North Andover, MA, United States, [2]Teachers College Columbia University, New York, NY, United States, [3]National Center for PTSD, VA Boston Healthcare System, Boston, MA, United States, [4]Department of Psychiatry, Boston University Chobanian & Avedisian School of Medicine, Boston, MA, United States, [5]Translational Research Center for TBI and Stress Disorders, VA Boston Healthcare System, Boston, MA, United States

Purpose: Psychological trauma can lead to PTSD which is associated with numerous negative health outcomes. Exercise has beneficial effects on PTSD; however, the amount of exercise associated with these benefits remains unknown. To examine self-reported exercise-related differences in PTSD symptom severity, psychological distress, pain, and sleep quality in a national sample of trauma-exposed adults.

Methods: Participants completed online assessments of exercise participation, PTSD symptom severity, psychological distress, pain, and sleep quality. Exercise level was defined as Active (≥24 on the Godin-Leisure Time Exercise Questionnaire [GLTEQ]), Insufficiently Active (1–23 on the GLTEQ), or Inactive (no reported exercise). MANCOVA was used to determine the relationship between exercise level (i.e., independent variable) and all outcomes (PTSD, distress, pain, sleep) with *post hoc* means comparison adjusted for age.

Results: Participants' (n = 500) mean age was 34.9 ± 13.0, and 68% were female. The overall model for exercise was significant, such that Active participants reported less PTSD symptom severity, psychological distress, and pain, and better sleep quality than Inactive participants.

Conclusion: Meeting the recommended amount of weekly physical activity with moderate-to-vigorous exercise is associated with better physical and mental health among trauma survivors. Longitudinal research is needed to confirm these cross-sectional findings.

KEYWORDS

posttraumatic stress disorder, physical activity, exercise, mental health, sleep, pain

1 Introduction

Post-traumatic stress disorder (PTSD) is a mental health disorder that affects roughly 12 million US adults each year (National Institutes of Mental Health, n.d.). PTSD develops after a traumatic event that can include (but are not limited to) violent physical assaults, natural (or human) disasters (Milligan-Saville et al., 2018), accidents, cardiac events

(Wilder Schaaf et al., 2013), partner- and sexual- violence (Dworkin et al., 2023), and/or military combat (Hughes et al., 2018). Although exposure to events like these are common (i.e., about one half of all U. S. adults will experience at least one traumatic event in their lives), not all trauma-exposed individuals develop PTSD (Hughes et al., 2018). However, trauma exposure can lead to disruptive subclinical PTSD symptoms, and when PTSD does occur it significantly impairs functioning and is associated with numerous negative health outcomes including psychological distress, physical pain, and poor sleep quality (Whitworth et al., 2017). In fact, individuals who develop PTSD are 80% more likely to develop other mental illnesses compared to those without PTSD (National Institutes of Mental Health, n.d.).

1.1 Psychological distress and PTSD

Regardless of the nature of the traumatic event, experiencing trauma can lead to psychological distress. For example, a 2013 systematic review found that following cardiac events, rates of depression ranged from 14 to 45% and anxiety from 13 to 61% (Wilder Schaaf et al., 2013). Observational findings from emergency service workers (i.e., police officer, fire fighter, paramedics) show that repeated trauma experience in the workplace can lead to significant and debilitating distress with rates as high at 10% in this study (Milligan-Saville et al., 2018). Further, another study analyzing data from 289,328 Iraq and Afghanistan veterans revealed that 50,432 (17.4%) received a clinical depression diagnosis with women experiencing a higher risk than men (Seal et al., 2009). Fortunately, a recent review highlights that among persons with differing traumatic experiences (e.g., first responders, natural disaster, fire fighters), the burden of distress can be attenuated through psychological interventions (Alshahrani et al., 2022). However, these types of interventions may be limited in accessibility and scalability. As such, strategies to reduce the burden of distress that are also highly scalable and sustainable are warranted.

1.2 Sleep quality and PTSD

Poor sleep quality (e.g., trouble falling and staying asleep, nightmares) is one of the hallmark symptoms of PTSD, is worse for those with co-occurring depressive symptoms (Weber et al., 2020), and results in more severe PTSD symptoms (Germain et al., 2004). Results from polysomnographic studies (i.e., a multimodal objective measure of sleep) among people with PTSD have observed rapid eye movement (REM) sleep attenuation and disruption (Baglioni et al., 2016) which is meaningful because REM sleep disturbances can threaten psychological resilience (Germain et al., 2004). Research exploring differences in diurnal rhythm between persons with PTSD compared to insomnia objectively demonstrates that persons with PTSD experience greater daily variability, stability and amplitude compared to persons with insomnia, with researchers suggesting one likely difference being unpredictable yet frequent nightmares (Mascaro et al., 2021). Still, poor sleep is a modifiable risk factor, and effective interventions that target sleep quality and potential nightmares as primary aims may expedite PTSD recovery.

1.3 Pain and PTSD

Pain is one of the most commonly reported physical symptoms of individuals with PTSD (Asmundson et al., 2002). Individuals who have pain from either a traumatic event (e.g., serious burns, physical assault) or morphological changes from a chronic disease (e.g., HIV) often report symptoms of PTSD (Asmundson et al., 2002). A documented range of 45–85% of patients who present for PTSD treatment also have a significant pain condition. The high co-prevalence of these conditions can lead to greater affective distress, interference in functioning and higher levels of disability than for those who live with either condition alone (Scioli et al., 2009). Thus, a better understanding of integrated treatment modalities that can complement existing evidence-based therapies for PTSD and/or pain to help manage and even mitigate such negative health consequences is needed.

1.4 Benefits of exercise for PTSD and related conditions

Exercise (i.e., purposeful physical activity done to improve health) has beneficial effects on PTSD and its negative health outcomes, including a reduction in trauma-related symptom severity and psychological distress. For example, observational, experimental, and qualitative evidence points to an inverse relationship between exercise and PTSD symptom severity (Whitworth and Ciccolo, 2016; Hegberg et al., 2019), with potential mechanisms that include exposure and desensitization to internal arousal cues (e.g., facilitating extinction), enhanced cognitive function, and reductions in inflammatory markers related to stress (Hegberg et al., 2019). Relationships between exercise, physical health conditions (e.g., pain) and other lifestyle-based behaviors (e.g., sleep) are understudied in trauma-exposed adults, reflecting the larger healthcare system in the United States which separates treatments for physical and mental conditions. However, several recent experimental trials demonstrate positive effects of exercise on PTSD symptoms and suggest benefits of exercise on sleep quality (Whitworth et al., 2019; Rosenbaum et al., 2015; Pebole et al., 2024). Increasing understanding of the relations among exercise, physical health and health promoting behaviors is relevant for creating integrated treatment approaches that incorporate exercise to improve functioning in physical and mental health domains.

However, the dose (i.e., amount) of exercise that is associated with a reduction in these negative outcomes is unclear. For instance, it is currently unknown if meeting the weekly physical activity guidelines set forth by the World Health Organization (i.e., 150 min/week or more of moderate-to-vigorous physical activity) (World Health Organization, 2018) with exercise is associated with physical and mental health among trauma-exposed adults. Understanding dose of exercise associated with better physical and mental health has significant implications for implementing exercise interventions and public health exercise promotion among communities exposed to trauma.

Thus, the purpose of this cross-sectional study was to examine exercise-related differences in PTSD symptom severity, psychological distress, pain, and sleep quality in a national sample of trauma-exposed adults. A more thorough understanding of the multifaceted links between these co-occurring symptoms and PTSD is timely in order to subsequently develop and deliver more targeted interventions.

We hypothesized that participants who self-reported a weekly amount exercise consistent with meeting the recommended levels of weekly physical activity would report less PTSD symptom-severity, pain and psychological distress, and better sleep quality, relative to individuals who reported insufficient levels of weekly exercise or no weekly exercise.

2 Materials and methods

2.1 Participants and procedures

Baseline data from a larger longitudinal study examining exercise and PTSD were analyzed for this exploratory secondary analysis. The complete methods of the parent study can be referenced elsewhere (Whitworth et al., 2017). In brief, potential participants were recruited from major metropolitan areas across all four US regions (i.e., Northeast, South, Midwest, and West). Recruitment was accomplished through online classifieds, such as Craigslist. The classified listings provided a brief description of the study and a link to the study's informed consent. Consenting individuals were then directed to an Internet platform and asked to complete a battery of questionnaires. To be eligible for the study, participants had to be living within the continental US, and have access to the Internet. All had to be at least 18 years in age, be able to read English, and report experiencing a traumatic event. However, disclosure of details relating to the trauma (e.g., trauma type, or when it occurred) were not required to participate. Individuals with additional histories of psychiatric illness other than PTSD (e.g., depression, anxiety, or substance use disorders) were not excluded from participation. Participants who did not meet these criteria based on an initial set of study questions were thanked for their participation but told they were ineligible at this time. Participants who completed the study were entered into a raffle to win a $50 gift card. The odds of winning were 1 in 25. The study was approved by the local Institutional Review Board at *blinded for review* and has been carried out in accordance with the Declaration of Helsinki. Data collection for this study between October 2015 and December 2016.

2.2 Measures

2.2.1 Demographics questionnaire

Demographic data were self-reported and included age, gender, race/ethnicity, living condition, employment status, sexual orientation, education, income, veteran status, and height and weight.

2.2.2 PTSD symptom severity

Post-traumatic stress disorder symptom severity was assessed with the PTSD Checklist-Civilian (PCL-C). The PCL-C is a 17-item, 5-point self-report scale used to assess PTSD symptom severity over the past month (Weathers et al., 1993). Items are ranked from "Not at all" to "Extremely" and correspond with the individual PTSD symptom clusters: re-experiencing, avoidance/numbing, and hyperarousal. Items are summed to represent a total PTSD symptom severity score. Valid total scores range from 17 to 85, with higher scores representing greater symptom severity. Scores of 30 or more are considered a positive screening for PTSD in the general US population. The PCL-C is a reliable and valid measure of PTSD symptom severity in numerous populations, including in the general public. It is strongly correlated with the Clinician Administered PTSD Scale (CAPS; $r = 0.93$) and is reliable when administered electronically (Campbell et al., 1999).

2.2.3 Psychological distress

The Kessler Psychological Distress Scale (K10) is a self-report scale which assesses overall psychological distress over the past 4 weeks (Kessler et al., 2002). Each of the 10-items contains five points ranging from "Never" to "All of the time." Valid scores range from 10 to 50, with higher scores representing greater levels of psychological distress. A score of 20 or more indicates a possible disorder causing psychological distress. The K10 is a valid and reliable measure of psychological distress (Kessler et al., 2002).

2.2.4 Sleep quality

Global sleep quality for the past month was assessed with the full Pittsburgh Sleep Quality Index (PSQI). The PSQI is a self-report 19-item scale that assesses seven components of sleep, including sleep quality, latency, duration, efficiency, disturbances, use of sleep medications, and daytime dysfunction (Buysse et al., 1989). Scores range from 0 to 21. Higher scores represent worse global sleep quality and a cut-point of > 5 indicates poor global sleep quality. The PSQI is a reliable and valid assessment of global sleep quality (Buysse et al., 1989).

2.2.5 Physical pain

Overall physical pain in the past month was assessed using the 2-item self-report Bodily Pain sub-scale of the Short Form Health Survey (Ware and Sherbourne, 1992). In this scale, the first item corresponds with pain intensity, consisting of 6-point ranking from "none" to "very severe." The second item represents the amount pain has interfered with work or activities of daily living, and it has a 5-point ranking from "not at all" to "extremely." Total scores range from 0 to 100 with lower scores representing more bodily pain. Scores less than 50 represent greater than average pain. The Pain sub-scale of the Short Form Health Survey is a simple, valid, and reliable measure of overall physical pain in the past month (Hawker et al., 2011).

2.2.6 Leisure-time exercise

Self-reported exercise behaviors were measured using the Godin-Shephard Leisure-Time Exercise Questionnaire (GLTEQ) (Godin and Shephard, 1985). The GLTEQ asks individuals to report, "During a typical 7-Day period (a week), how many times on average do you do the following kinds of exercise for more than 15 min during your free time." This was asked for strenuous (e.g., vigorous running or cycling), moderate (e.g., non-exhaustive sports, jogging, or weight training), and minimal intensity exercise (e.g., yoga, or easy walking). The GLTEQ is scored by multiplying the frequency of strenuous, moderate, and minimal intensity exercise by corresponding metabolic equivalent values 9, 5, and 3, respectively. For interpretation, individuals who achieved a score of ≥24 from either moderate, or strenuous intensity exercise, or a combination of both (i.e., total leisure-time exercise) were classified as "Active" and were likely to have met the weekly physical activity recommendations of ≥150 min/week of moderate-to-vigorous intensity physical activity (Amireault and Godin, 2015). Individuals who scored > 0 but < 24 were considered "Insufficiently Active" (i.e., reported some weekly leisure-time exercise, but below the recommended levels). Individuals who reported no weekly exercise (i.e., a score of 0) were categorized as "Inactive." The GLTEQ is a reliable and valid measure of total leisure-time exercise, as well as strenuous, moderate, and minimal intensity exercise (Amireault and Godin, 2015).

2.3 Data analysis

Descriptive statistics were used to describe the aggregate sample and are presented as mean (standard deviation) for continuous variables and n (percentage) for categorical variables. As a preliminary step, associations between potential confounders, (e.g., demographics) and predictor (i.e., exercise) and outcome (i.e., PTSD symptom severity, psychological distress, pain, sleep quality) were considered. Pearson's *r* was used for continuous variables and chi-square tests were used for categorical variables. Any variable significantly associated with both outcome and predictor were considered confounders and adjusted for in the subsequent analyses.

Multivariate analysis of variance was then conducted to determine the overall relationship between exercise participation (i.e., independent variable) and PTSD symptom severity, pain, psychological distress, and sleep quality (i.e., dependent variables). In our preliminary step, we found that age was a significant confound, thus, a multivariate analysis of covariance was conducted adjusting for age.

Lastly, pairwise comparisons of exercise level (i.e., Active = GLTEQ score ≥24; Insufficiently Active = GLTEQ score of 1–23; and Inactive = GLTEQ score of 0) for each dependent variable were conducted with Bonferroni correction. The threshold for statistical significance was $p < 0.050$.

3 Results

A total of 741 individuals enrolled in the study. Five hundred participants completed the baseline electronic survey and were included in the final analyses. Of the 239 individuals excluded from the study, 107 consented to participate, but did not respond to any question (i.e., there is no descriptive data on them). A comparison of the remaining 132 individuals excluded from the final analysis to those who were included, found they were significantly more likely to identify as male ($p < 0.05$). However, there were no other observed significant differences between those included and excluded. See Table 1 for a complete description of the sample characteristics, and Table 2 for a summary of PTSD symptom severity, pain, psychological distress, and sleep quality organized by activity level. In brief, participants' mean age was 34.9 (13.0) years and body mass index was 27.8 (7.5). Most participants identified as female (68.8%), White (69.2%), heterosexual (73.6%), and were non-Latino/a (84.4%). Almost half (48.4%) of the participants were considered Active, 25.6% and Insufficiently Active, and 26.0% Inactive. The mean PCL-C score was 55.7 (16.4), K10 30.6 (9.7), physical pain 61.7 (27.7), and PSQI 10.6 (4.5).

The assumptions of equality of covariance matrices and error variances were evaluated with Box's M ($p > 0.05$) and Levene's Test (all *p*'s, > 0.05), respectively. The overall multivariate model for exercise was significant, $F(8, 986) = 3.71$, $p < 0.001$; Wilk's $\lambda = 0.942$. Results for the between-subjects tests were significant for dependent variables: PTSD symptom severity [$F(2, 496) = 7.98$, $p < 0.001$], psychological distress [$F(2, 496) = 7.54$, $p = 0.001$], physical pain [$F(2, 496) = 4.79$, $p = 0.009$], and sleep quality [$F(2, 496) = 11.89$, $p < 0.001$]. Age was a significant covariate for PTSD symptom severity, psychological stress, and physical pain (*p*'s < 0.050), but not sleep quality ($p = 0.329$). Complete results for the pairwise comparisons can be found in Table 3. In summary, individuals who were Active, reported significantly less PTSD symptom severity, psychological distress, pain, and better sleep quality, relative to Inactive participants (*p*'s < 0.010). Additionally, individuals who were Insufficiently Active reported significantly less PTSD symptom severity and better sleep quality than Inactive participants (*p*'s < 0.050). Insufficiently Active and Active individuals did not differ significantly for any dependent variable (*p*'s > 0.050).

4 Discussion

The purpose of this online observational study was to explore relationships between level of self-reported exercise (i.e., Inactive, Insufficiently Active, and Active), PTSD symptom severity, psychological distress, physical pain, and sleep quality. We hypothesized that a greater amount of exercise would be associated with lower PTSD symptom severity, less psychological distress, less pain, and better sleep quality among trauma-exposed individuals. Indeed, the results showed that Active participants reported significantly lower PTSD symptoms, psychological distress, less pain, and better sleep quality than those who reported being Inactive. While cross-sectional, these results may support the importance of trauma-exposed individuals meeting the recommended amount of weekly physical activity through exercise (i.e., consistent with a score ≥24 on the GLTEQ, or ≥150 min per week of moderate-to-vigorous intensity exercise). Another key finding of this study is Insufficiently Active individuals also reported significantly lower PTSD symptoms and better sleep quality than Inactive participants, which provides preliminary support for a dose–response relationship between exercise, PTSD symptoms and sleep quality.

These findings largely support the results of research in related areas. For instance, a recent large study of exercise dose and generalized anxiety disorder (GAD) from The Irish Longitudinal Study on Ageing (TILDA) reported a dose–response relationship between moderate-to-vigorous exercise participation and the risk for GAD (Herring et al., 2024). Importantly, the largest reported decrease in risk for GAD was seen among individuals transitioning from inactive (i.e., no reported exercise) to insufficiently active (i.e., some exercise, but less than recommended amounts). Similar results for physical activity and depression were published in a recent meta-analysis (Pearce et al., 2022). Specially, a dose–response effect of physical activity on risk for depression, with the largest observed benefit going from inactive to insufficiently active. This mirrors our findings for PTSD symptom severity and sleep quality (see Table 3). In contrast, we did not observe significant differences in bodily pain and psychological distress between the Inactive and Insufficiently Active groups, or between the Insufficiently Active and Active groups. However, Active individuals did report significantly less psychological distress and bodily pain

TABLE 1 Sample characteristics (*n* = 500).

Characteristic	*n* (%)
Gender	
Male	134 (26.8)
Female	344 (68.8)
Transgender	16 (3.2)
Other	6 (1.2)
Race	
American Indian/Alaskan Native	14 (10.4)
Asian/ Native Hawaiian or Pacific Islander	42 (8.4)
Black or African American	42 (8.4)
White	346 (69.2)
Other/Do not know	56 (11.2)
Latino/a	78 (15.6)
Education	
High school or less	70 (14.0)
Some college/vocational school	135 (27.0)
Completed college/vocational school	295 (59.0)
Employment status	
Full-time	167 (33.4)
Part-time	90 (18.0)
Unemployed	112 (22.4)
Student	61 (12.2)
Other	70 (14.0)
Household income	
$25,000 or less	196 (39.2)
$25,001–$60,000	141 (28.2)
$60,001–$100,000	87 (17.4)
$100,001 or more	41 (8.2)
Do not know	35 (7.0)
Military veteran (Yes)	65 (13.0)
Sexual orientation	
Heterosexual	368 (73.6)
Homosexual	40 (8.0)
Bisexual	67 (13.4)
Other	25 (5.0)
Physical activity status	
Inactive	130 (26.0)
Insufficiently Active	128 (25.6)
Active	242 (48.4)
Psychiatric history	
PTSD	311 (62.2)
Anxiety disorder	281 (56.2)
Depression	316 (63.2)
Schizophrenia	16 (3.2)
Bipolar disorder	75 (15.0)
Alcohol use disorder	30 (6.0)
Substance use disorder	32 (6.4)

	Mean (standard deviation)
Age	34.9 (13.0)
Body mass index (*n* = 316)	27.8 (7.5)
PCL-C	55.7 (16.4)
K10	30.6 (9.7)
Chronic pain	61.7 (27.7)
PSQI	10.6 (4.5)

PCL-C = PTSD Checklist Civilian; K10 = Kessler Psychological Distress Scale; PSQI = Pittsburgh Sleep Quality Index. Height and weight data were collected on 316 participants, so body mass index could not be calculated for the entire sample.

than Inactive individuals. These results are largely consistent with the field, suggesting that exercise has a beneficial effect on both pain (Geneen et al., 2017) and psychological distress (Singh et al., 2023).

An important characteristic of this study is that multifaceted approach to evaluating associations between exercise and physical and mental health, rather than evaluated PTSD, psychological distress, pain, and sleep quality in isolation. This is critical, as there are high rates of comorbidity among individuals with psychiatric disorders, insomnia and pain. This is clearly demonstrated in our sample where on average PTSD symptom severity, psychological distress and pain were elevated, and sleep quality was poor.

The association of exercise and multiple components of mental and physical health has potentially broad implications for exercise as a tool in the treatment and prevention of PTSD and related conditions. Stress and coping theory help provide a useful framework these relationships (Folkman and Moskowitz, 2004). Specifically, it is possible that exercise may be a useful pluripotent coping strategy for clinicians to promote physical and mental wellness for trauma survivors. Exercise may also be an opportunity for trauma survivors have an element of control and autonomy in their mental and physical health journey (e.g., choosing what types of exercise to do, where, when, and with whom (Sheppard-Perkins et al., 2022; Pebole et al., 2021)). As some studies suggest, regular exercise participation may reduce PTSD symptom severity, distress, lessen pain, and improve global sleep quality (Hegberg et al., 2019; Whitworth et al., 2019; Rosenbaum et al., 2015). However, it is equally plausible that the combined influence of poor mental health, insomnia, and physical pain, prevent regular exercise to a greater extent than each condition independently (Morasco et al., 2013; Talbot et al., 2014). In fact, some research supports this, suggesting that individuals affected by these conditions, or having greater symptom severity of these conditions, are less likely to exercise (Hall et al., 2015; Hall et al., 2020). For example, individual with severe PTSD may be more likely to rely on avoidance or numbing based coping strategies (e.g., avoiding busy public spaces, like gyms or parks, and/or isolation/distancing). Perhaps the most likely scenario is a combination of both cases, such that both exercise and an individual's current health simultaneously exert their influence in a bidirectional game of tug-of-war. It is therefore recommended that researchers who are interested in developing

TABLE 2 Group-level summary statistics for PTSD symptoms, psychological distress, chronic pain, and sleep.

Activity status	PTSD symptoms	Psychological distress	Chronic pain	Sleep quality	
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	n
Inactive	59.9 (15.7)	32.6 (9.3)	54.5 (28.3)	12.2 (4.7)	130
Insufficiently Active	55.4 (15.0)	31.1 (9.0)	61.8 (25.2)	10.2 (4.1)	128
Active	53.6 (17.2)	29.3 (10.1)	65.5 (28.0)	9.9 (4.5)	242

SD = standard deviation; total n = 500.

TABLE 3 Pairwise comparison between PTSD, distress, pain, and sleep, by physical activity status.

Dependent variable	PA level comparison	Mean difference (95% CI)	SE	*p*-value
PTSD symptoms	Inactive vs. Insufficiently active	5.29 (0.38, 10.19)	2.04	0.030*
	Inactive vs. Active	7.11 (2.82, 11.41)	1.79	<0.001**
	Insufficiently active vs. Active	1.83 (−2.41, 6.08)	1.77	0.904
Psychological distress	Inactive vs. Insufficiently Active	2.24 (−0.64, 5.11)	1.20	0.188
	Inactive vs. Active	4.05 (1.53, 6.57)	1.05	<0.001**
	Insufficiently Active vs. Active	1.81 (−0.69, 4.30)	1.04	0.246
Chronic pain	Inactive vs. Insufficiently Active	−5.45 (−13.68, 2.77)	3.42	0.336
	Inactive vs. Active	−9.25 (−16.44, −2.05)	3.00	0.006**
	Insufficiently Active vs. Active	−3.80 (−10.92, 3.33)	2.97	0.604
Sleep quality	Inactive vs. Insufficiently Active	2.08 (0.73, 3.43)	0.53	0.001**
	Inactive vs. Active	2.33 (1.15, 3.51)	0.49	<0.001**
	Insufficiently Active vs. Active	0.25 (−0.92, 1.42)	0.49	0.999

PTSD = posttraumatic stress disorder; PA = physical activity; CI = confidence interval; SE = standard error. * and ** Denote statistical significance at $p < 0.050$ and $p < 0.010$, respectively. *P*-values were adjusted for multiple comparisons, using Bonferroni correction factor.

exercise interventions for trauma-exposed adults consider this bi-directional relationship and offer support, particularly for those who are sedentary, to engage these individuals more effectively in exercise.

There were several strengths and limitations to this study. First, we recruited a national sample of trauma-exposed adults. This increases the external validity of our findings to a greater extent than data from treatment-seeking adults from a hospital setting. Secondly, the GLTEQ is a validated assessment of exercise that can be a reliable way to gauge whether participants are meeting the recommended weekly amount of physical activity set forth by the World Health Organization. Further, the GLTEQ helps to extend findings from previous exercise and PTSD research which have focused heavily on single-item measures of exercise (Hegberg et al., 2019). Despite these strengths, this study has limitations. First, the data used in this study is cross-sectional, thus the directionality of the observed relationships cannot be determined from this study alone. Further, this was a secondary analysis, and the results should be considered exploratory and not confirmatory. The observational and online study design also presents some challenges. For example, despite sampling from all regions of the United States, the data is not nationally representative, and certain demographics are likely over-represented (e.g., non-Hispanic White women), while others are likely under-represented (e.g., Black men). Indeed, analysis of the individuals who did not complete the study, suggests they were more likely to identify as male. Other factors, such as the low compensation for participation (i.e., a gift card raffle) may have deterred some individuals from participating. As such, these data may not generalize to all peoples, especially harder to reach populations, and those without an internet connection (e.g., some rural communities and individuals without stable housing). The self-report nature of this study may also subject the data to recall biases and other inaccurate reporting associated with self-report data collection (Haskell, 2012). Further, the measurement of pain in this study is limited to pain in the past month and cannot determine if the reported physical pain was chronic (i.e., lasting more than 12 weeks). As previously described, pain commonly co-occurs with PTSD and is known to further interfere with functioning. As such, more comprehensive assessment of pain is recommended in future physical activity and PTSD research.

5 Conclusion

Greater amount of self-reported exercise is cross-sectionally associated with lower PTSD symptom severity, less psychological distress, physical pain, and better sleep quality among trauma-exposed adults. Meeting the recommended amount of weekly physical activity with moderate-to-vigorous exercise is associated with the largest differences. However, achieving some weekly exercise but not meeting the recommended amount (i.e., Insufficiently Active) was also associated lower PTSD symptom severity and better sleep quality than no physical activity.

Practical Implications and Future Directions: The results of this study suggest even small amounts of exercise (i.e., less than the recommended weekly dose of exercise) may be beneficial for trauma-exposed individuals – something is better than nothing. This is encouraging, and supports individuals becoming more active gradually, over time, at their own pace.

Future studies are needed to examine the longitudinal course of exercise participation among trauma-exposed individuals to determine its potential role in the treatment and prevention of PTSD, and related conditions. This work would be further enhanced by more detailed investigations of the parameters of exercise, For instance, comparisons between exercise mode (e.g., aerobic and resistance exercise), as well as patient/trauma survivor exercise preferences.

Data availability statement

The dataset presented in this article is not readily available because of security protocols and privacy regulations, but they may be made available on reasonable request by the VA Boston Healthcare System or by contacting the corresponding author to facilitate the request.

Ethics statement

The studies involving humans were approved by Teachers College Columbia University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

NS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing. EC: Writing – original draft, Writing – review & editing. MP: Writing – original draft, Writing – review & editing. JW: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. JW is supported by a VA Rehabilitation Research & Development Career Development Award (5IK2RX003564). MP funded by postdoctoral fellowship from office of academic affairs and US Department of Veterans Affairs.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Alshahrani, K. M., Johnson, J., Prudenzi, A., and O'Connor, D. B. (2022). The effectiveness of psychological interventions for reducing PTSD and psychological distress in first responders: a systematic review and meta-analysis. *PLoS One* 17:e0272732. doi: 10.1371/journal.pone.0272732

Amireault, S., and Godin, G. (2015). The Godin-Shephard leisure-time physical activity questionnaire: validity evidence supporting its use for classifying healthy adults into active and insufficiently active categories. *Percept. Mot. Skills* 120, 604–622. doi: 10.2466/03.27.PMS.120v19x7

Asmundson, G. J., Coons, M. J., Taylor, S., and Katz, J. (2002). PTSD and the experience of pain: research and clinical implications of shared vulnerability and mutual maintenance models. *Can. J. Psychiatr.* 47, 930–937. doi: 10.1177/070674370204701004

Baglioni, C., Nanovska, S., Regen, W., Spiegelhalder, K., Feige, B., Nissen, C., et al. (2016). Sleep and mental disorders: a meta-analysis of polysomnographic research. *Psychol. Bull.* 142, 969–990. doi: 10.1037/bul0000053

Buysse, D. J., Reynolds, C. F. III, Monk, T. H., Berman, S. R., and Kupfer, D. J. (1989). The Pittsburgh sleep quality index: a new instrument for psychiatric practice and research. *Psychiatry Res.* 28, 193–213. doi: 10.1016/0165-1781(89)90047-4

Campbell, K. A., Rohlman, D. S., Storzbach, D., Binder, L. M., Anger, W. K., Kovera, C. A., et al. (1999). Test-retest reliability of psychological and neurobehavioral tests self-administered by computer. *Assessment* 6, 21–32. doi: 10.1177/107319119900600103

Dworkin, E. R., Jaffe, A. E., Bedard-Gilligan, M., and Fitzpatrick, S. (2023). PTSD in the year following sexual assault: a Meta-analysis of prospective studies. *TVA* 24, 497–514. doi: 10.1177/15248380211032213

Folkman, S., and Moskowitz, J. T. (2004). Coping: pitfalls and promise. *Annu. Rev. Psychol.* 55, 745–774. doi: 10.1146/annurev.psych.55.090902.141456

Geneen, L. J., Moore, A. R., Clarke, C., Martin, D., Colvin, L. A., and Smith, B. H. (2017). Physical activity and exercise for chronic pain in adults: an overview of Cochrane reviews. *Cochrane Database Syst. Rev.* 1. doi: 10.1002/14651858.CD011279.pub3

Germain, A., Buysse, D. J., Shear, M. K., Fayyad, R., and Austin, C. (2004). Clinical correlates of poor sleep quality in posttraumatic stress disorder. *J. Trauma. Stress.* 17, 477–484. doi: 10.1007/s10960-004-5796-6

Godin, G., and Shephard, R. J. (1985). A simple method to assess exercise behavior in the community. *Can. J. Appl. Sport Sci.* 10, 141–146.

Hall, K. S., Hoerster, K. D., and Yancy, W. S. Jr. (2015). Post-traumatic stress disorder, physical activity, and eating behaviors. *Epidemiol. Rev.* 37, 103–115. doi: 10.1093/epirev/mxu011

Hall, K. S., Morey, M. C., Bosworth, H. B., Beckham, J. C., Pebole, M. M., Sloane, R., et al. (2020). Pilot randomized controlled trial of exercise training for older veterans with PTSD. *J. Behav. Med.* 43, 648–659. doi: 10.1007/s10865-019-00073-w

Haskell, W. L. (2012). Physical activity by self-report: a brief history and future issues. *J. Phys. Act. Health* 9, S5–S10. doi: 10.1123/jpah.9.s1.s5

Hawker, G. A., Mian, S., Kendzerska, T., and French, M. (2011). Measures of adult pain: visual analog scale for pain (VAS pain), numeric rating scale for pain (NRS pain), McGill pain questionnaire (MPQ), short-form McGill pain questionnaire (SF-MPQ), chronic pain grade scale (CPGS), short Form-36 bodily pain scale (SF-36 BPS), and measure of intermittent and constant osteoarthritis pain (ICOAP). *Arthritis Care Res (Hoboken).* 63, S240–S252. doi: 10.1002/acr.20543

Hegberg, N. J., Hayes, J. P., and Hayes, S. M. (2019). Exercise intervention in PTSD: a narrative review and rationale for implementation. *Front. Psych.* 10. doi: 10.3389/fpsyt.2019.00133

Herring, M. P., Rasmussen, C. L., McDowell, C. P., Gordon, B. R., Kenny, R. A., and Laird, E. (2024). Physical activity dose for generalized anxiety disorder & worry: results from the Irish longitudinal study on ageing. *Psychiatry Res.* 332:115723. doi: 10.1016/j.psychres.2024.115723

Hughes, J. M., Ulmer, C. S., Hastings, S. N., Gierisch, J. M.Mid-Atlantic VA MIRECC Workgroup, and Howard, M. O. (2018). Sleep, resilience, and psychological distress in United States military veterans. *Mil. Psychol.* 30, 404–414. doi: 10.1080/08995605.2018.1478551

Kessler, R. C., Andrews, G., Colpe, L. J., Hiripi, E., Mroczek, D. K., Normand, S. L. T., et al. (2002). Short screening scales to monitor population prevalences and trends in non-specific psychological distress. *Psychol. Med.* 32, 959–976. doi: 10.1017/S0033291702006074

Mascaro, L., Phillips, A. J., Clark, J. W., Phillips, A. J. K., Straus, L. D., and Drummond, S. P. A. (2021). Diurnal rhythm robustness in individuals with PTSD and insomnia and the association with sleep. *J. Biol. Rhythm.* 36, 185–195. doi: 10.1177/0748730420984563

Milligan-Saville, J., Choi, I., Deady, M., Scott, P., Tan, L., Calvo, R. A., et al. (2018). The impact of trauma exposure on the development of PTSD and psychological distress in a volunteer fire service. *Psychiatry Res.* 270, 1110–1115. doi: 10.1016/j.psychres.2018.06.058

Morasco, B. J., Lovejoy, T. I., Lu, M., Turk, D. C., Lewis, L., and Dobscha, S. K. (2013). The relationship between PTSD and chronic pain: mediating role of coping strategies and depression. *Pain* 154, 609–616. doi: 10.1016/j.pain.2013.01.001

National Institutes of Mental Health. Post-traumatic stress disorder (PTSD). Available online at: https://www.nimh.nih.gov/health/statistics/post-traumatic-stress-disorder-ptsd (Accessed on March 11, 2022)

Pearce, M., Garcia, L., Abbas, A., Strain, T., Schuch, F. B., Golubic, R., et al. (2022). Association between physical activity and risk of depression: a systematic review and Meta-analysis. *JAMA Psychiatry* 79, 550–559. doi: 10.1001/jamapsychiatry.2022.0609

Pebole, M., Gobin, R. L., and Hall, K. S. (2021). Trauma-informed exercise for women survivors of sexual violence. *Transl. Behav. Med.* 11, 686–691. doi: 10.1093/tbm/ibaa043

Pebole, M. M., SantaBarbara, N. J., Nosrat, S., and Whitworth, J. W. (2024). Effects of resistance training on mental health and sleep outcomes among women with posttraumatic stress disorder. *Pract. Innov.* 9, 30–38. doi: 10.1037/pri0000216

Rosenbaum, S., Sherrington, C., and Tiedemann, A. (2015). Exercise augmentation compared with usual care for post-traumatic stress disorder: a randomized controlled trial. *Acta Psychiatr. Scand.* 131, 350–359. doi: 10.1111/acps.12371

Scioli, E. R., Otis, J. D., and Keane, T. M. (2009). Psychological problems associated with operation enduring freedom/operation Iraqi freedom deployment. *Am. J. Lifestyle Med.* 4, 349–359. doi: 10.1177/1559827610362962

Seal, K. H., Metzler, T. J., Gima, K. S., Bertenthal, D., Maguen, S., and Marmar, C. R. (2009). Trends and risk factors for mental health diagnoses among Iraq and Afghanistan veterans using Department of Veterans Affairs health care, 2002-2008. *Am. J. Public Health* 99, 1651–1658. doi: 10.2105/AJPH.2008.150284

Sheppard-Perkins, M. D., Malcolm, S. K., Hira, S. K., Smith, S. V. M., and Darroch, F. E. (2022). Exploring moderate to vigorous physical activity for women with post-traumatic stress disorder: a scoping review. *Ment. Health Phys. Act.* 23:100474. doi: 10.1016/j.mhpa.2022.100474

Singh, B., Olds, T., Curtis, R., Dumuid, D., Virgara, R., Watson, A., et al. (2023). Effectiveness of physical activity interventions for improving depression, anxiety and distress: an overview of systematic reviews. *Br. J. Sports Med.* 57, 1203–1209. doi: 10.1136/bjsports-2022-106195

Talbot, L. S., Neylan, T. C., Metzler, T. J., and Cohen, B. E. (2014). The mediating effect of sleep quality on the relationship between PTSD and physical activity. *J. Clin. Sleep Med.* 10, 795–801. doi: 10.5664/jcsm.3878

Ware, J. E., and Sherbourne, C. D. (1992). The MOS 36-item short-form health survey (SF-36). I. Conceptual framework and item selection. *Med. Care* 30, 473–483.

Weathers, F., Litz, B., Herman, D., Huska, J., and Keane, T. (1993). The PTSD checklist (PCL): reliability, validity, and diagnostic utility. Annual convention of the international society for traumatic stress studies, San Antonio, TX

Weber, F. C., Norra, C., and Wetter, T. C. (2020). Sleep disturbances and suicidality in posttraumatic stress disorder: an overview of the literature. *Front. Psych.* 11. doi: 10.3389/fpsyt.2020.00167

Whitworth, J. W., and Ciccolo, J. T. (2016). Exercise and post-traumatic stress disorder in military veterans: a systematic review. *Mil. Med.* 181, 953–960. doi: 10.7205/MILMED-D-15-00488

Whitworth, J. W., Craft, L. L., Dunsiger, S. I., and Ciccolo, J. T. (2017). Direct and indirect effects of exercise on posttraumatic stress disorder symptoms: a longitudinal study. *Gen. Hosp. Psychiatry* 49, 56–62. doi: 10.1016/j.genhosppsych.2017.06.012

Whitworth, J. W., Nosrat, S., SantaBarbara, N. J., and Ciccolo, J. T. (2019). Feasibility of resistance exercise for posttraumatic stress and anxiety symptoms: a randomized controlled pilot study. *J. Trauma. Stress.* 32, 977–984. doi: 10.1002/jts.22464

Wilder Schaaf, K. P., Artman, L. K., Peberdy, M. A., Walker, W. C., Ornato, J. P., Gossip, M. R., et al. (2013). Anxiety, depression, and PTSD following cardiac arrest: a systematic review of the literature. *Resuscitation* 84, 873–877. doi: 10.1016/j.resuscitation.2012.11.021

World Health Organization. Global action plan on physical activity 2018-2030: more active people for a healthier world. (2018). Availiable onilne at https://www.who.int/publications/i/item/9789241514187. (Accessed March 22, 2022).

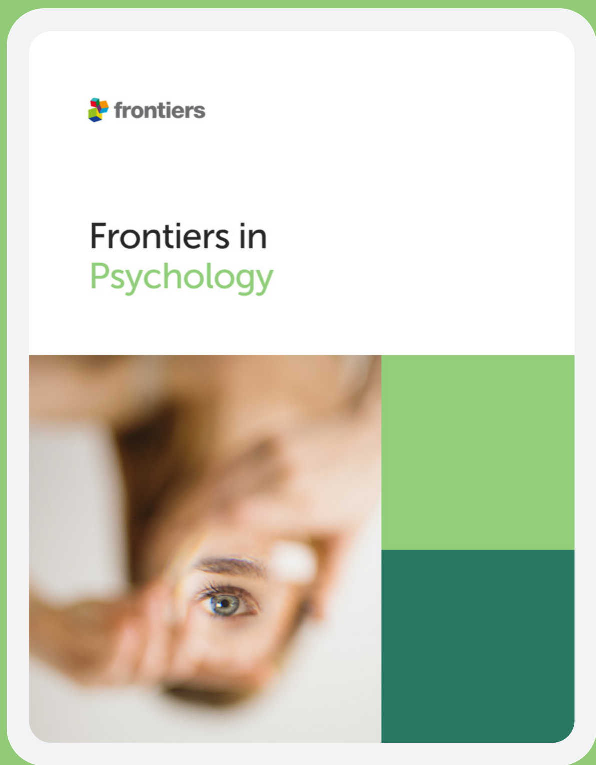
Frontiers in Psychology

Paving the way for a greater understanding of human behavior

The most cited journal in its field, exploring psychological sciences - from clinical research to cognitive science, from imaging studies to human factors, and from animal cognition to social psychology.

Discover the latest Research Topics

See more →



Frontiers

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

Contact us

+41 (0)21 510 17 00
frontiersin.org/about/contact