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Physical activity attenuates negative effects of short-term exposure to ambient air pollution on cognitive function

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ABSTRACT

Background: As physical activity benefits brain health whereas air pollution damages it, the cognitive response to these exposures may interact.
Purpose: This study aimed to assess the short-term joint effect of physical activity and air pollution on cognitive function in a panel of healthy young adults.
Methods: We followed ninety healthy subjects aged around 22 years from September 2020 to June 2021 and measured their personal exposure to fine particulate matter ($PM_{2.5}$) ($\mu g/m^3$) and daily accelerometer-based moderate-to-vigorous physical activity (MVPA) (min/day) in 4 one-week-long sessions over the study period. At the end of each measurement session, we assessed executive function using Stroop color-word test and collected resting-state electroencephalogram (EEG) signals.
Results: We found short-term $PM_{2.5}$ exposure damaged executive function ($\beta_{PM25} = 0.0064$, $p = 0.039$) but physical activity could counterbalance it ($\beta_{MVPA} = -0.0047$, $p = 0.048$), whereby beta-3 wave played as a potential mediating role. MVPA-induced improvement on executive function was larger in polluted air ($\beta_{MVPA} = -0.010$, $p = 0.035$) than that in clean air ($\beta_{MVPA} = -0.003$, $p = 0.45$). To offset the negative effect of air pollution on cognitive function, individuals should do extra 13.6 min MVPA every day for every 10 $\mu g/m^3$ increase in daily $PM_{2.5}$.
Conclusion: This study implies that physical activity could be used as a preventive approach to compensate the cognitive damages of air pollution.

1. Introduction

It is widely acknowledged that physical activity induces various health benefits, such as reducing all-cause and cardiovascular mortalities (Lee et al., 2012; Stewart et al., 2017), decreasing the incidence of chronic diseases, including coronary heart disease, diabetes and hypertension (Allegretti and Thadhani, 2018; Diaz and Shimbo, 2013; Rognmo et al., 2012), improving mental health (Chekroud et al., 2018; Stubbs et al., 2018), promoting healthy aging (Gopinath et al., 2018), and others (Febbraio, 2017; Neufer et al., 2015). Also, extensive studies have demonstrated that physical activity benefits brain health and improves cognitive function in healthy individuals and people with neurodegenerative diseases (Barha et al., 2017; Hillman et al., 2008; Raichlen and Alexander, 2017). Moreover, moderate-to-vigorous physical activity (MVPA) (e.g., high-intensity interval training) exerts neuroprotection effects on human brains in a time-efficient way (Calverley et al., 2020; Mekari et al., 2020). According to several human and animal studies, the underlying mechanism of physical activity induced health benefits includes elevated brain-derived neurotrophic factor (BDNF) secretion (Coelho et al., 2013; Hwang et al., 2016), enhanced neurogenesis and neuroplasticity (Lista and Sorrentino, 2010; Vaynman et al., 2004), increased gray matter volume and functional connectivity

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of hippocampus (Aly and Kojima, 2020; Killgore et al., 2013), which thereby benefits the central nervous system (Aguiar et al., 2011; Hötting and Röder, 2013). In contrast to physical activity, air pollution results in multiple adverse health effects and leads to over three million premature deaths per year worldwide (Bowe et al., 2018; Lelieveld et al., 2015). Fine particulate matter, particles with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$), enters circulation system, triggers cytokine release, and indirectly impairs blood brain barrier, or directly trans-locates to the central nerve system via olfactory bulb (Bos et al., 2014). Recently, growing evidence has suggested an association between air pollution exposure and impaired cognitive function, probably due to elevated oxidative stress and neuroinflammation (Chen and Schwartz, 2009; Zhang et al., 2018). While putting two categories of studies together, an intriguing question is whether physical activity in polluted air still benefits cognitive function. On one hand, due to an increased ventilation rate, the inhalation of harmful particles may considerably increase when individuals do physical activity in a polluted environment, potentially enhancing the deleterious effects of air pollution on cognitive function (Int Panis et al., 2010). On the other hand, physical activity can induce anti-inflammatory effect, which may counteract the proinflammatory effect of air pollution (Bos et al., 2014; Lista and Sorrentino, 2010), and elevate cerebrovascular oxygen level and blood supply, potentially protecting cognitive function (Calverley et al., 2020; Lucas et al., 2015).

Some existing studies explored the joint effect of air pollution and physical activity. One animal study demonstrated attenuated benefits of acute physical activity due to exposure to high levels of $PM_{2.5}$ via declined BDNF expression in hippocampus (I. Bos et al., 2012), but another study found insignificant reduction of BDNF in a similar study setting (Inge Bos et al., 2012). Some epidemiological studies found that short-term physical activity and air pollution jointly influenced lung function (Laeremans et al., 2018b, 2018a) and micro-vascular function (Weichenthal et al., 2014), but independently influenced systemic inflammation (Zhang et al., 2018) and blood pressure (Avila-Palencia et al., 2019). In the long term, significant interaction was observed in metabolic syndrome and lung function (Fuertes et al., 2018; Hou et al., 2020). In addition, an ecological study found that the benefit of aerobic training on executive function was attenuated due to exposure to traffic-related ultrafine particles (Bos et al., 2013), but a cross-over study demonstrated that physical activity had beneficial effects on pulmonary function even when performed in a highly polluted environment (Kubesch et al., 2015). However, previous studies on the joint effect of air pollution and physical activity remain inconsistent, and few studies explored the joint effect on cognitive function, especially among healthy young adults who are more physically active.

Therefore, the current study focused on the joint effect of physical activity and air pollution on cognitive function and attempted to quantify how to use physical activity to compensate the damage induced by air pollution. We followed ninety healthy young adults in a longitudinally repeated study design. We measured individual-level physical activity using accelerometer, calculated MVPA as the metric of physical activity, and measured personal exposure to $PM_{2.5}$ using portable monitors. We also assessed executive function as one metric of cognitive function based on the classic Stroop color-word test and collected resting-state electroencephalogram (EEG) signals. We analyzed the joint effect using mixed-effect model and explored potentially neural mechanism using mediation analysis. Hence, the aim of the current study was to (1) evaluate individual-level and joint effects of real-life daily MVPA and $PM_{2.5}$ exposure on executive function in a sample of healthy young adults; (2) recommend the appropriate dose of MVPA to compensate the adverse effect of $PM_{2.5}$. We believe this study can deepen our understanding on the interaction between air pollution and physical activity, and further provide recommendations on how to take exercise in a polluted environment.

2. Methods

2.1. Study design and participants

The current study adopted a longitudinally repeated study design to explore the interaction of individual-level MVPA and short-term air pollution exposure on executive function among healthy young adults, based on evidence from behavior tests and resting-state EEG signals. In this longitudinal study, repeated measurement sessions were carried out four times between September 2020 and June 2021, with 79, 79, 72 and 71 participants attending, respectively. In each round of measurement session, subjects were instructed to wear an accelerometer and carry a portable real-time environmental monitor for a week while performing their daily activities. At the end of each measurement session, they were instructed to complete computer-based tasks on the day of returning equipment at a research center of Tsinghua University, China. Tasks included a five-minute closed-eyes resting state test with EEG and a classic Stroop color-word test.

Before this study, we posted recruitment information for this study on the Internet. People who were interested completed a questionnaire on medical history and demographical information. The selection criteria of this study were that: (1) young adults aged between 18 and 30; (2) right-handed; (3) free from motor diseases and any of the medical conditions listed on the widely-used Physical Activity Readiness Questionnaire (PAR-Q) (Thomas et al., 1992); (4) free from cardiovascular, cerebrovascular, respiratory, or neurological diseases (history); (5) with normal or corrected-to-normal vision; (6) receiving or having received higher education; (7) with ability to read and understand Chinese smoothly; (8) non-smoker. Finally, a total of ninety volunteers from Beijing, China, were included in this study and all of them completed at least two repeated measurement sessions. Ethical approval was obtained from the Institutional Review Board of Tsinghua University (ID number: 20190091). All participants were asked to give written informed consent before starting the study. A total of 200, 300 and 500 RMB (equivalent to 31, 47 and 78 American dollars) was offered to participants if they finished two, three and four sessions of measurements.

2.2. Physical activity assessment

Physical activity was measured with the ActiGraph accelerometer (model wGT3X-BT, USA) on a one-minute basis (Peters et al., 2010). Participants wore the accelerometer on the left wrist for seven consecutive days except when getting wet (e.g., bathing, showering, swimming etc.). Average time spent on MVPA per day (in minutes) during the wearing week was adopted as the physical activity indicator in this study. According to Freedson algorithm (Freedson et al., 1998), MVPA was defined as greater than 1,952 counts per minute. Wearing the accelerometer for at least three days and at least 10 h per day was considered valid and used for follow-up analysis (van Berkel et al., 2013). In addition, participants were asked to keep activity diaries on the time that they started wearing and taking off the accelerometer. Non-wearing periods were determined by a threshold of greater than 30 min with 0 counts/minute and adjunctively identified with participants' accelerometry diaries. Physical activity data was preprocessed online using ActiLife 6 version 5.5. Finally, there are 78, 79, 72 and 71 valid accelerometer data in four sessions of measurements, respectively.

2.3. Assessment of personal exposure to air pollution

We used individual-level exposure to $PM_{2.5}$ as the metric of personal exposure to air pollution. Exposure to $PM_{2.5}$ was measured on a personal level using a portable monitor produced by ecofive (model ECO-12, Laimi Electronic Technology (Shanghai) Co., Ltd, China). The portable monitor works as following: surrounding air is drawn over a glass fiber filter at a stable flow rate of 100 mL/min, resulting in $PM_{2.5}$ accumulation on the filter; the device checks $PM_{2.5}$ by detecting the changing optical absorption of light transmitted through filter at wavelength of 880 nm. The $PM_{2.5}$ measurement range is 0–999 ug/m^3 with resolution 1 $\mu g/m^3$. The portable monitor records the average $PM_{2.5}$ concentration on a one-minute basis. In each round of the measurement session, participants were instructed to carry the device with them for seven consecutive days indoors and outdoors. While indoor, participants were asked to place the portable monitor at the height of 80–120 cm with good ventilation without influence from humidifier and chimney. While outside, the portable monitor was packed in a string bag with holes, so participants could carry the device conveniently while it measured ambient $PM_{2.5}$. Raw $PM_{2.5}$ data of each person were averaged on daily basis. Data with an error code due to filter saturation or flow out of range were excluded. Averaged daily $PM_{2.5}$ concentration was calculated for the entire seven days of each measurement session.

2.4. Assessment of executive function and collection of EEG signals

EEG is a non-invasive, cheap and convenient method to explore the electrocortical activity of human brains, and has been applied extensively as it can capture temporary cortical changes related to various cognitive functioning, such as memory and inhibition control (Gramkow et al., 2020; Rossini et al., 2019). Previous studies found that the resting-state EEG signals, such as band power of alpha and beta waves, were closely correlated with neurological activities and could be significantly influenced by health-related behaviors (e.g., sleep and exercise) (Lardon and Polich, 1996). In addition, in recent years, Stroop test has been widely used to investigate the inhibition control ability, which is considered as an important anti-interference process of executive function (West and Alain, 1999). In this study, a computer-based test was adapted, which was programmed using PsychoPy (Peirce, 2007), consisted of a 5-minute EEG-based eyes-closed resting-state task and a series of modified Stroop color-word tasks referred to previous studies (Chang et al., 2015; Hsieh et al., 2018). Subjects sat comfortably in a quietly isolated room and were asked to remain still when test began. Spontaneous EEG was first recorded for five-minute eyes-closed and two-minute eyes-open resting conditions. Then, they were required to perform a 15-minute Stroop test following the instructions. The Stroop test consisted of three types of trials: congruent, incongruent and neutral. Congruent trials used one of four color words (i.e., "蓝" (Chinese character for *blue*), "绿" (Chinese character for *green*), "黄" (Chinese character for *yellow*) and "红" (Chinese character for *red*)) printed in Chinese language in the corresponding ink color (e.g., "绿" (green) was printed in green). The incongruent trials consisted of the same four words, but printed in non-corresponding colors (e.g., "绿" (green) was printed in red). The neutral trails were written in the form of "XXXX" with four ink color (e.g., "XXXX" was printed in yellow). Five blocks of trials constituted the Stroop test used in our study. Each block comprised of 24 trials, including 12 incongruent, 8 congruent and 4 neutral trials, displayed randomly. Before the formal testing, a practice block with 20 trials including 12 incongruent, 4 congruent and 4 neutral trials was provided to participants to help them get familiar with the rules. The stimuli were 5 × 5 cm and were displayed focally on the center of a 32-inch computer monitor that was placed 80 cm in front of participants. Each trial began with the fixation (+) being presented randomly for 400–600 ms. Participants were instructed to indicate the color of the presented stimuli as fast as possible within a 1000 ms response window by pressing keys with their left hand as follows: "D" for blue and "F" for green, and right hand: "J" for red and "K" for yellow. Each trial interval was 600 ms. The schematic diagram of the Stroop test can be seen in Fig. S1. Mean response time of correct trials (CRT, s) under three different stimulus conditions were calculated as the indicator of executive function at the behavioral level. In Stroop test, we used correct response time as the metric instead of accuracy, because it combines both response accuracy and response time, and thus reflects executive function change in a better way.

EEG activity was recorded with 32 electrode sites embedded in an electrode cap (Neuracle, Borui Kang Technology (Changzhou) Co., Ltd., China) according to the International 10–20 system (Jasper H H, 1958) (Fig. S2). Prior to the EEG recordings, electrode impedance was maintained at 10 kΩ or below as recommended for high impedance amplifiers (Ferree et al., 2001). Online, continuous data were referenced to FCz electrode with the ground electrode AFz. The continuous online data acquisition was digitized at a 1000 Hz sampling rate and were amplified 1000 times with a 50-Hz Butterworth second-order notch filter using Neuracle (model NSW364) amplifier. Offline, continuous EEG data were preprocessed using EEGLAB toolbox plugins in MATLAB (R2020b) (Delorme and Makeig, 2004). EEG data were firstly re-referenced to averaged mastoids (TP9, TP10) and then filtered with a zero-phase shift of 0.5–30 Hz band-pass cutoff. Ocular artifacts were corrected using Independent Component Analysis (ICA) (Jung et al., 2000). Recordings were finally taken from thirty electrodes (Cz, Fz, Fp1, F7, F3, FC1, C3, FC5, T7, CP5, CP1, P3, P7, O1, Pz, Oz, O2, P8, P4, CP2, CP6, T8, FC6, C4, FC2, F4, F8, Fp2, FT9, FT10). After signal preprocessing, the 5-min eyes-closed resting state EEG was segmented into a series of two-second epochs and then the absolute power of signals in different frequency bands was calculated. The mean absolute band power (μV^2), using as the EEG activity indicator, was analyzed with Welch algorithm in obtaining delta (1–3 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta-1 (13–16 Hz), beta-2 (17–23 Hz) and beta-3 (23–30 Hz) frequency bands. Considering alpha and beta waves are prominent when an individual is awake while delta and theta waves are normally observed during sleep, we only assessed changes in alpha and beta waves in the current study (Kan and Lee, 2015; Posada-Quintero et al., 2019). Those epochs with large interference noises (amplitude greater than 100 μV) within two seconds would be removed. The range of frequency bands were defined according to a previous study (Laufs et al., 2003).

2.5. National air pollution assessment and physical activity recommendations

Annual $PM_{2.5}$ Data was downloaded from "Tracking Air Pollution in China database" (TAP, http://tapdata.org.cn/) for the year 2020 (Wei et al., 2021). The methodology of $PM_{2.5}$ assessment of this dataset can be found elsewhere (Xiao et al., 2018). Considering the annual $PM_{2.5}$ exposure standard recommended by China is less than 35 $\mu g/m^3$, the excessive $PM_{2.5}$ exposure for people in different provinces was the difference between the annual $PM_{2.5}$ exposure of each province in 2020 and 35 $\mu g/m^3$. Therefore, the additionally recommended daily MVPA was calculated by multiplying the difference by the risk–benefit trade-off relationship between $PM_{2.5}$ and MVPA (i.e., recommended MVPA $_{daily}$ = (annual $PM_{2.5}$ - 35) × risk–benefit coefficient).

2.6. Statistical analysis

R software version 3.6.3 was used for data processing and analysis. Considering the longitudinally repeated study design, we employed a mixed-effect model with a random effect on individuals to account for between-individual variation. Time-invariant variables were controlled by such study design. We estimated the short-term effects of $PM_{2.5}$, MVPA and their interactions on executive function outcomes of interest (R-packages: lme4 and nlme4 (Lindstrom and Bates, 1988)). We used $PM_{2.5}$ level three days before (i.e., lag 3) as the metric of $PM_{2.5}$ based on Akaike Information Criterion (AIC) value (supplementary Table S1). To help interpret results, we also took a logarithm transform on the dependent variable to calculate the percentage change associated with ten units change in independent variable, as shown in the form of percentage in parentheses. In addition, since $PM_{2.5}$ and MVPA may interacted in a non-linear way, we further conducted subgroup analysis with trisecting air pollution levels (i.e., good, fair, and bad). The executive function improvement associated with ten units change in MVPA was calculated for good and bad air qualities, respectively. Furthermore, we explored the mediation effect of EEG signals on the association between

$PM_{2.5}$, MVPA and correct response time to discover the possibly underlying influence mechanism, using a R package called mediation (Imai et al., 2010).

We preformed analyses in both crude and adjusted models (Table S2 and S3). Crude models were (1) with MVPA only, (2) with $PM_{2.5}$ only, and (3) with MVPA × $PM_{2.5}$. Adjusted models were (1) with MVPA and confounders, (2) with $PM_{2.5}$ and confounders, and (3) with MVPA × $PM_{2.5}$ and confounders. Throughout the results, we referred to β as the model estimate and used Kenward-Roger's approximation for the calculation of *p*-values (Luke, 2017). Adjusted models, shown in the text, controlled for confounding variables such as gender, age, educational levels, height, temperature, and humidity. P value less than 0.05 were considered statistically significant and less than 0.1 were borderline significant.

3. Results

3.1. Demographic information and pollution distribution.

Among the total of 90 participants, 60 of them completed all four measurement sessions; 1 participant completed three rounds of measurement sessions; 29 participants completed two. About half of the participants were males (48.89%). Participants were on average of 22.29 ± 2.28 years old, 170.47 ± 8.08 cm tall, had BMI of 21.91 ± 3.98 kg/m^2, and had received higher education of 4.86 ± 1.78 years (Table 1). For Stroop test, the correct response time for incongruent stimulus condition (0.64 ± 0.15 s) was longer than that of congruent (0.58 ± 0.11 s) and neutral stimulus (0.59 ± 0.12 s) (Table 1).

Daily $PM_{2.5}$ exposure during measurement sessions was below 120 μg/m^3, with average concentration of 26.3 μg/m3 (Fig. 1 A). Air pollution level in Beijing, China, has declined profoundly in recent years, but still exceeded the daily $PM_{2.5}$ exposure standard of 25 μg/m^3 recommended by World Health Organization (WHO) (Krzyzanowski and Cohen, 2008) (Fig. 1 A). Physical activity of each individual was assessed with the ActiGraph accelerometer during the one-week-long measurement session, and the average daily MVPA was around 114 min, which exceeded the minimal recommended health security of 30 min by WHO (Fig. 1 B).

3.2. Physical activity attenuates the negative impact of air pollution on executive function.

In adjusted models, every 10 μg/m^3 increase in $PM_{2.5}$ was significantly associated with an increase of 0.0064 s (increased by 0.95%) in incongruent correct response time (β_{PM25} = 0.0064, p = 0.039). The incongruent correct response time significantly improved by 0.0047 s (decreased by 0.62%) for every 10 min increase of MVPA per day (β_{MVPA} = −0.0047, p = 0.048), indicating that for every 10 μg/m^3 increase of daily $PM_{2.5}$ exposure, 13.6 min of MVPA per day was needed to offset the negative effects of $PM_{2.5}$ on executive function (Fig. 2 A). Coefficients of $\beta_{MVPA\times PM25}$ were not statistically significant but less than zero, indicating that MVPA might attenuate the cognitive impact of every unit increase in $PM_{2.5}$ exposure. Such linear interaction was not significant, probably due to limited sample size (Fig. 2 A). Crude models demonstrated similar trends (Table S2).

3.3. Physical activity demonstrated greater protective effect during polluted days

We assessed the dose–response relationships between correct response time, MVPA and $PM_{2.5}$ by fitting a generalized additive model with splines (R-package: GAM (Vicendese et al., 2013)). Effects of MVPA on correct response time were almost downward linear while effects of $PM_{2.5}$ on it seemed to be non-linear. The effect of $PM_{2.5}$ on correct reaction time was larger when the concentration was below 20 or above 60 μg/m^3 (Figs. 3 and S3). To deal with the possible nonlinear relationship, we performed subgroup analysis by categorizing air pollution into three levels (i.e., poor, fair, and good). In adjusted models, when air quality was poor, MVPA demonstrated significant improvement effect on executive function under the incongruent stimulus condition (β_{MVPA} = -0.010, p = 0.035, 1.25%) (Fig. 2 B). Crude models indicated similarly borderline significant results (Table S3). Nonetheless, the beneficial effect of MVPA on executive function diminished when air quality was good (β_{MVPA} = -0.003, p = 0.45, 0.47%) (Table S3). In other words, MVPA-induced improvement on executive function was larger in polluted air than that in clean air (Fig. S4).

3.4. Beta-3 wave mediates the effect of air pollution and physical activity on executive function

Furthermore, we explored the effect estimates of MVPA, $PM_{2.5}$ and their interaction on the absolute band power in alpha, beta-1, beta-2 and beta-3 waves to explore possible neurological mechanisms. The topographic map indicated that absolute alpha power was larger in the central and parietal lobe for physically active participants, regardless of air pollution levels (Fig. 4 (a)). According to the adjusted mixed-effect analysis, the absolute power of alpha wave showed a statistically significant increase of 0.85, 0.69, 1.77, 2.08, 1.42 and 1.06 μV^2 (increased by 2.84%, 1.99%, 3.47%, 3.63%, 3.28%, and 2.85% respectively) in the CP5, CP6, P3, P4, Pz and CP2 electrodes with an increase of 10 min per day in MVPA. Notably, MVPA also significantly decreased the absolute power of beta-3 wave in the FC5 electrode (β_{MVPA} = −0.080, p = 0.020, 3.32%). In addition, the beta-2 and beta-3 waves in the whole brain scalp seemed to be activated in poor air (Fig. 4 (c-d)). For instance, a significant increase of 0.26 and 0.21 μV^2 (3.43% and 3.89%) in beta-2 band power was observed in Cz and Fz electrodes with a 10 μg/m^3 increase of $PM_{2.5}$. Similarly, the positive association of $PM_{2.5}$ with beta-3 in that Cz and Fz electrodes was also observed (β_{PM25} = 0.11, p = 0.017,

Table 1
Demographic characteristics and cognitive behavioral outcomes of study populations.

Variables	Overall (n = 90)	1st experiment (n = 79)	2nd experiment (n = 79)	3rd experiment (n = 72)	4th experiment (n = 71)
Demographics					
Men	44 (48.89%)	37 (46.84%)	37 (46.84%)	37 (51.39%)	37 (52.11%)
Age (years)	22.29 ± 2.28	22.16 ± 2.24	22.16 ± 2.24	22.10 ± 2.01	22.10 ± 2.02
Weight (kg)	64.37 ± 14.60	64.04 ± 14.51	64.04 ± 14.51	64.36 ± 13.84	64.51 ± 13.88
Height (cm)	170.47 ± 8.08	170.31 ± 8.06	170.31 ± 8.06	170.85 ± 8.13	171 ± 8.08
BMI (kg/m^2)	21.91 ± 3.98	21.86 ± 4.03	21.86 ± 4.03	21.74 ± 3.46	21.75 ± 3.48
Higher education (years)	4.86 ± 1.78	4.84 ± 1.86	4.84 ± 1.86	4.75 ± 1.55	4.76 ± 1.56
Executive function					
Behavioral level					
Congruent CRT (s)	0.58 ± 0.11	0.62 ± 0.11	0.59 ± 0.10	0.56 ± 0.10	0.54 ± 0.094
Incongruent CRT (s)	0.64 ± 0.15	0.70 ± 0.16	0.66 ± 0.14	0.61 ± 0.13	0.58 ± 0.14
Neutral CRT (s)	0.59 ± 0.12	0.64 ± 0.15	0.60 ± 0.11	0.57 ± 0.10	0.54 ± 0.087

Note: BMI, body mass index; CRT, correct response time. Continuous variable results are reported as Mean ± Standard deviation, and results of classified variables are expressed in n (%).

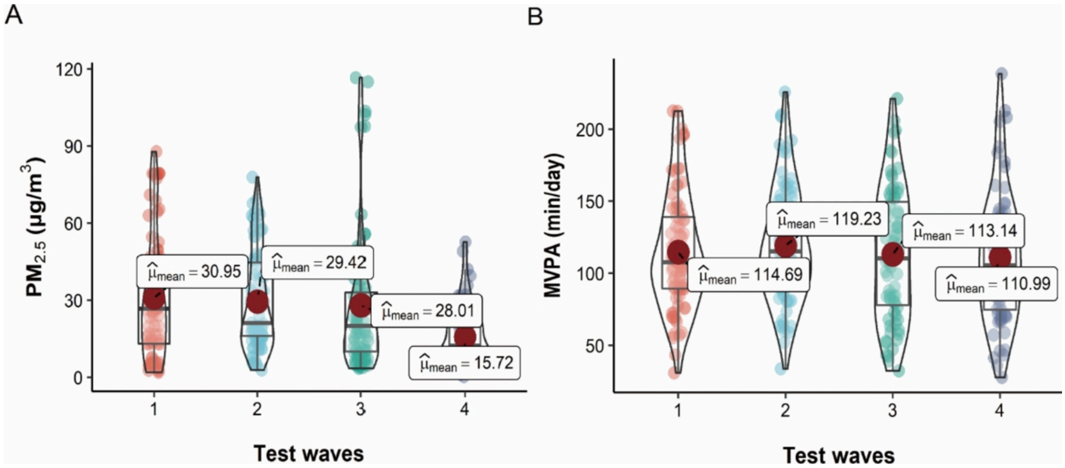

Fig. 1. Exposure results of $PM_{2.5}$ concentration and MVPA of four measurement sessions aggregated per participant. MVPA, moderate-to-vigorous physical activity; $\overline{\mu}_{mean}$, mean estimation. Subgraph (A) and (B) indicated the day-level $PM_{2.5}$ exposure concentration (μg/m^3) and averaged MVPA (min/day) in the week before each round of measurement session.

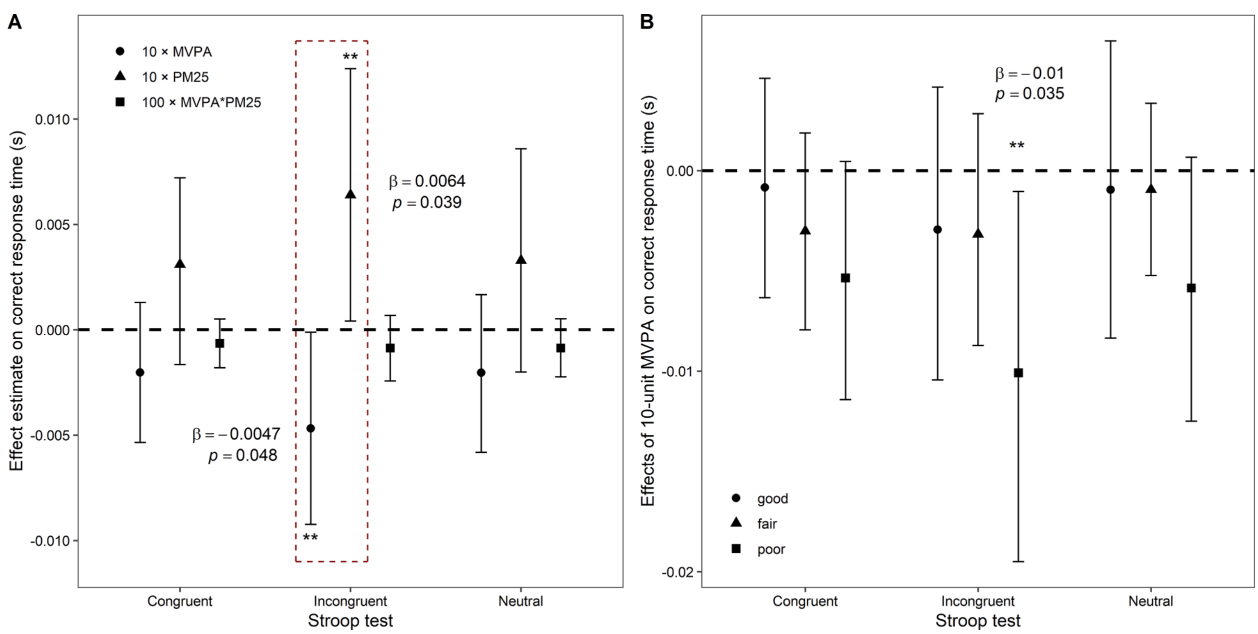

Fig. 2. Results of the adjusted mixed-effect model and subgroup analysis on the cognitive behavioral outcomes of executive function. β, effect estimate; MVPA, averaged daily moderate-to-vigorous physical activity; PM_{25}, personal daily $PM_{2.5}$ exposure. Subgraph (A) indicated the effect estimates of 10 min/day increase of MVPA (circle) and 10 μg/m^3 increase of $PM_{2.5}$ (triangle) as well as their interaction (square) on correct response time under congruent, incongruent and neutral stimulus conditions. Subgraph (B) indicated the subgroup effect estimates of 10 min/day increase of MVPA on three kinds of correct response time under trisecting air pollution levels, with good air (circle) being less than 13.6 μg/m^3, fair (triangle) being between 13.6 and 28.1 μg/m^3, and poor (square) being over 28.1 μg/m^3. In both subgraph (A) and (B), error line showed 95% confidence interval. Adjusted models included confounders of gender, age, educational levels, height, temperature-lag0 and humidity-lag0. ** $p < 0.05$.

4.74%; $\beta_{PM25} = 0.089$, $p = 0.034$, 4.69%). Moreover, it was interesting to find that the beta-3 wave played a mediator role between $PM_{2.5}$, MVPA and behavioral performance of executive function, with over 15% mediation proportion (Fig. 5). Of note, for every 10 μg/m^3 increase in daily $PM_{2.5}$, the incongruent correct response time indirectly increased about 1.4 ms (increased by 0.33%); while for every 10 min/day increase in MVPA, the incongruent correct response time indirectly decreased around 0.62 ms (decreased by 0.17%) (Fig. 5).

3.5. Physical activity recommendations based on ambient air pollution concentrations

Above results imply that physical activity can be used as a preventive approach to compensate the cognitive impact of air pollution. Based on this idea, we calculated the recommended MVPA dose for residents in different Chinese provinces given the local air pollution levels, based on the quantitively relationship between $PM_{2.5}$, MVPA and executive function. The provincial $PM_{2.5}$ concentration in China was obtained from an online database for the year 2020 based on the averaged daily $PM_{2.5}$ exposure (http://tapdata.org.cn/) (Wei et al., 2021). The annual $PM_{2.5}$ exposure in central China regions was highest (around 70 μg/m^3), such as in Hunan and Shanxi provinces (Fig. 6 A). Provinces in Northern China, such as Liaoning, Hebei, Tianjin, also had relatively high $PM_{2.5}$ pollution (>60 μg/m^3), except for Beijing, where the annual $PM_{2.5}$ exposure improved recently (<50 μg/m^3) (Fig. 6 A). Hence, people living in Beijing and Hunan are recommended to take 19 and 53 min

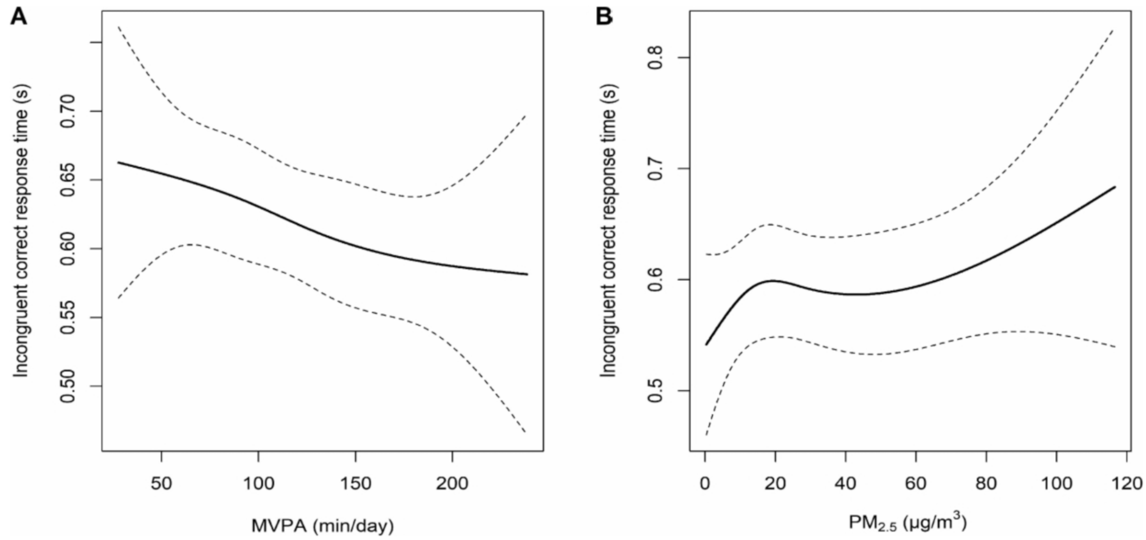

Fig. 3. Dose-response relationships between incongruent correct response time, MVPA and $PM_{2.5}$. These dose–response curves were fitted in generalized additive models with splines by using R-package "GAM" (Onywera, 2010). MVPA, averaged daily moderate-to-vigorous physical activity; PM25, personal daily $PM_{2.5}$ exposure. Subgraph (A) and (B) indicated the dose–response associations of incongruent correct response time with MVPA and $PM_{2.5}$, respectively. The downward trend of correct response time indicated better cognitive behavioral performance of executive function.

additional MVPA every day to offset $PM_{2.5}$ exposure, respectively (Fig. 6 B). Due to higher air pollution level, residents in Hunan provinces are recommended to take more exercise to compensate the negative effect of air pollution. Fig. 6 and Table S4 display recommended MVPA doses for other provinces. Detailed calculation process can be found in the Method Section.

4. Discussion

In this longitudinal study, we (1) investigated the separate and joint effects of objectively-measured short-term air pollution exposure and MVPA on executive function, and use EEG to explore the potential underlying mechanism; (2) gave recommendations on whether to take physical activity on polluted days, and further quantified the MVPA dose to compensate the adverse health effect of air pollution. MVPA could directly improve executive function while $PM_{2.5}$ damage it. Mediation analysis indicated that MVPA could also indirectly improve executive function by declining the absolute power of beta-3 band in frontal lobe, while $PM_{2.5}$ reduce executive function by elevating the absolute power of beta-3 band in the whole cerebral cortex. Moreover, the protective effect for each unit increase in MVPA on executive function was larger in poor air quality than that in good air quality. More importantly, we recommended that within a certain $PM_{2.5}$ concentration range, for every 10 μg/m^3 increase in daily $PM_{2.5}$, extra 13.6 min/day MVPA were effective to counterbalance the harmful effects of air pollution on executive function. This study suggests that physical activity could serve as a cost-effective and convenient preventive approach to compensate the adverse health effect of air pollution. We believe this result is particularly useful for other developing countries where air pollution is still rampant.

As expected, short-term exposure to $PM_{2.5}$ was associated with worsened correct response time of Stroop test, whereas the correlation with MVPA was in the opposite direction. Previous studies have some clues about the biological mechanism: particulate matter could translocate from the upper respiratory tract to the brain, resulting in neuroinflammation, blood–brain barrier destruction and microglial activation changes, which can induce cognitive impairment, attention deficit disorder, and even Alzheimer's disease (Block and Calderón-Garcidueñas, 2009; Gatto et al., 2014; Power et al., 2011; Ranft et al., 2009; Suglia et al., 2007). For physical activity, its protective role on cognitive function is related to increased secretion of BDNF and insulin-like growth factor 1 (IGF-1), increased volume and enhanced functional connectivity of hippocampus (Aly and Kojima, 2020; Burdette, 2010; Coelho et al., 2013; Hwang et al., 2016; Lista and Sorrentino, 2010). Moreover, MVPA (e.g., high-intensity interval training) has proved to have more remarkable neuroprotection potentiation effects from molecular, cellular and behavioral levels compared to light intensity physical activity (e.g., walking) (Calverley et al., 2020; Lista and Sorrentino, 2010; Mekari et al., 2020).

Although the linear interaction between $PM_{2.5}$ and MVPA remain to be insignificant, MVPA demonstrates different effect on executive function at different pollution levels, suggesting that a non-linear interaction exists between $PM_{2.5}$ and MVPA. This partially explains why previous studies achieved inconsistent results on the interaction between $PM_{2.5}$ and MVPA: several studies found that short-term physical activity and air pollution had jointly and opposite effects on respiratory markers (Laeremans et al., 2018a, 2018b) but independently influenced systemic inflammation (Zhang et al., 2018); while in the long term, physical activity and air pollution jointly influenced metabolic syndrome(Hou et al., 2020) and atherosclerotic cardiovascular disease (Tu et al., 2020). These inconsistent results may be due to non-linear interaction between air pollution and physical activity, which suggests future investigators to explicitly take non-linear interaction into account.

Despite of inconsistent results on the interaction, this study and previous studies all provide epidemiological evidence that physical activity serves like "therapy" and can prevent adverse effect induced by exposure to air pollution (Cole-Hunter et al., 2016; Hou et al., 2020; Laeremans et al., 2018a; Zhang et al., 2018). This statement is further supported by animal studies. For example, one animal study found that long-term aerobic exercise attenuated oxidative stress induced by air pollution and presented protective effects on lung inflammation (Vieira et al., 2012). However, recent researches indicated that the improving effect of physical activity on health outcomes seemed to be under a certain air pollution threshold. For instance, it was claimed that when $PM_{2.5}$ concentration was less than 22 μg/m^3 benefits of physical activity towards all-cause mortality by far outweighed risks from air pollution even doing vigorous exercise, but if living in highly polluted areas with $PM_{2.5}$ being more than 100 μg/m^3 harms would exceed benefits after 90 min or 10 h of cycling and walking per day, respectively (Giallouros et al., 2020). Similarly, another study found that the relationship between optimal moderate-intensity physical activity duration and $PM_{2.5}$

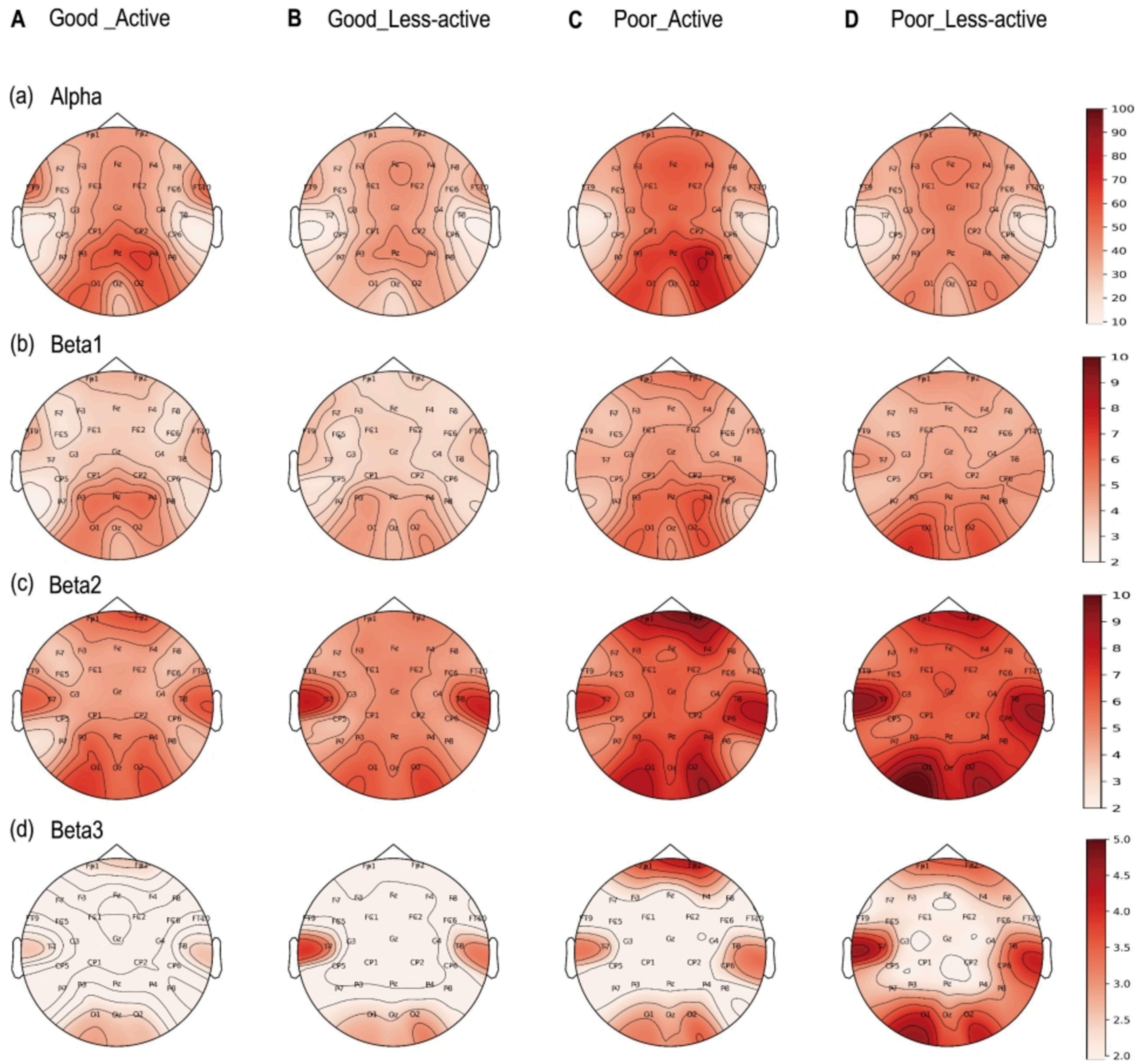

Fig. 4. Topographic map of the absolute alpha (a), beta-1 (b), beta-2 (c), and beta-3 (d) band powers according to the International 10–20 system in both good air and active MVPA level (A), both good air and less-active MVPA level (B), both poor air and active MVPA level (C), as well as both poor air and less-active MVPA level (D). MVPA, averaged daily moderate-to-vigorous physical activity. The higher the absolute band power of alpha and beta waves is, the redder the color of topographic map is. The good and poor air categories were separated according to the trisection air pollution levels, with good air being less than 13.6 μg/m^3 and poor air being over 28.1 μg/m^3. The active and less-active levels were divided according to the medium value of MVPA with 110 min/day being the cut-off. For instance, subgraph (A.a) showed the topographic map of absolute band power in alpha waves in the good air condition among active participants.

concentration levels were inverse non-linear, indicating that doing more physical activity was not always beneficial to health (An et al., 2020). Previous studies focused on the joint effect on the physiological aspect, we further achieved similar result on the cognitive function and brain health. Based on our study, even though it is possible to inhale more particulate matter while taking exercising in mild-to-moderate polluted air with average annual $PM_{2.5}$ being less than 100 μg/m^3, taking MVPA is still recommended to keep cognitive function and even brain health. The benefits of physical activity are way beyond the potential adverse effects on cognitive function. This finding was consistent with a long-term six-city-specific study, including Beijing, China, indicating that everyday active commuting reduced all-cause mortality even on days with high air pollution and stay home sedentarily was not actually good for reducing all-cause mortality risks (Giallouros et al., 2020).

Based on our study, we found that extra 13.6 min/day MVPA was recommended to maintain executive function for every 10 μg/m^3 increase in $PM_{2.5}$. According to this risk–benefit dose–response relationship, we put forward suggestions for people living in different provinces in China with different exposure concentration of air pollution. In 2020, the most polluted province in China is Hunan, with an average annual $PM_{2.5}$ concentration of 74.3 μg/m^3, and the capital of China, Beijing, presents an average annual $PM_{2.5}$ exposure of 48.9 μg/m^3, which are considered as moderate and mild air pollution levels in China. Hence, for people living in Beijing, extra 19 min MVPA was recommended every day to offset $PM_{2.5}$ exposure, while for the highest polluted province, Hunan, additionally daily 53 min MVPA was recommended. Of note, although it is difficult for people in some highly-polluted areas to keep full compliance with the recommended additional dose of MVPA, it should be emphasized that every extra minute of MVPA is beneficial: it can counteract some of the negative effect of $PM_{2.5}$ exposure. It is worth noting that above advice on physical activity is based on the air pollution levels observed in our study; extrapolating our results to other countries with heavier pollution deserves further investigation.

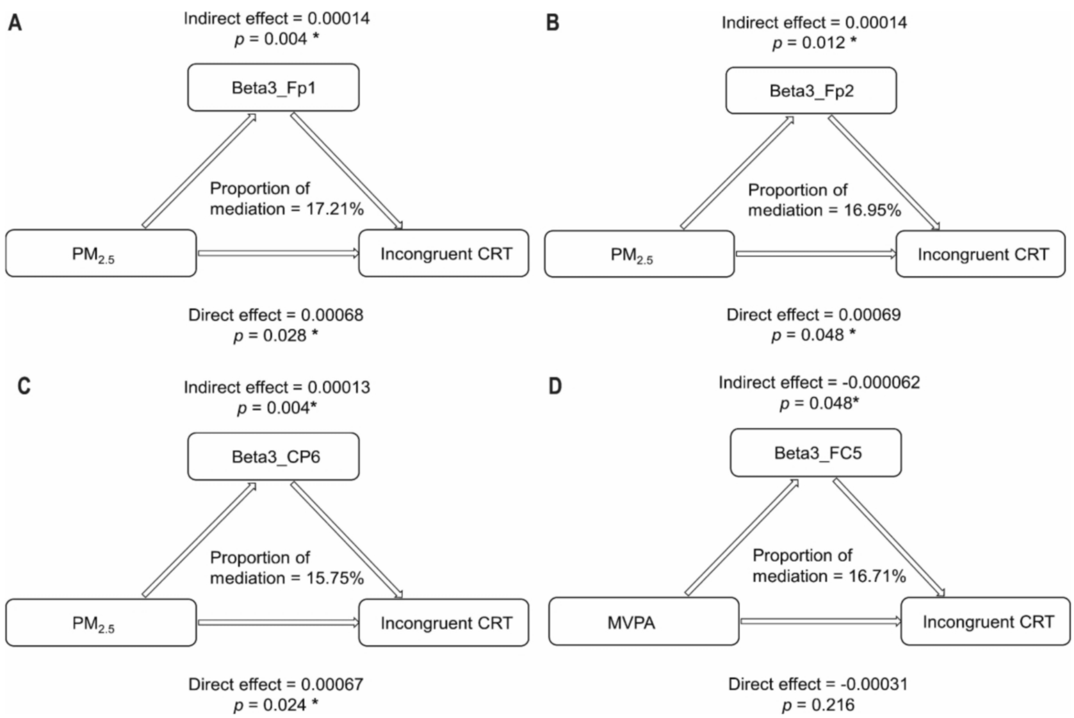

Fig. 5. Mediation effects of beta-3 wave on the relationship between $PM_{2.5}$, MVPA and incongruent correct response time. MVPA, averaged daily moderate-to-vigorous physical activity; CRT, correct response time. The subgraph (A-C) indicated the indirect influencing path of $PM_{2.5}$ on incongruent correct response time with beta-3 of Fp1, Fp2 and CP6 electrodes playing as a mediator, respectively. The subgraph (D) showed the indirect influencing path of MVPA on incongruent correct response time with beta-3 of FC5 electrode playing as a mediator. In subgraph (D), indirect effect = -0.000062 means that for every 1 min increase in the daily MVPA, there was an indirect reducing effect of 0.000062 s on the incongruent correct response time (i.e., for every 10 min/day increase in MVPA, the incongruent correct response time indirectly decreased around 0.62 ms), indicating an increased performance of executive function. The same interpretation also holds for other subgraphs. Calculation of mediation effects and proportion of mediation was completed in the mediation package of R software, version 3.6.3 with unadjusted mixed-effect models applied. * $p < 0.05$.

Furthermore, we found that MVPA could significantly increase the alpha band power, and reduce beta-3 band power and thereby improve executive function performance. This finding was consistent with previous studies revealing that physical exercise substantially affects resting-state EEG (Lardon and Polich, 1996; Wu et al., 2020); exercise could increase alpha and reduce beta activity with less anxiety and fatigue but more relaxed and attentive mind (Henz and Schöllhorn, 2017). Nonetheless, one study demonstrated that the enhancement of beta wave could improve neurofeedback and cognitive function in patients with mild cognitive impairment, which seemed to contradict this study (Jang et al., 2019). We supposed that increasing beta band power within a reasonable range might make individuals with attention deficit more alert and focused, but excessive increase result in elevated psychological load, thereby leading to worsened cognitive function performance. In addition, we found that beta band power, especially the beta-3 band power, could be amplified significantly with the increasing concentration of short-term $PM_{2.5,}$ and thus result in declining cognitive performance. Few studies have documented the associations between air pollution and changes in EEG signals so far. Therefore, this finding is worthy of attention. The intervention on alpha and beta-3 waves (e.g., music therapy) may be a new approach to keep brain healthy for people living in polluted regions.

This study has several limitations. First, our sample consisted of healthy, highly educated young adults with active physical activity level that exceeds much of the minimal health recommendation by WHO. Thus, our findings might not be extrapolated to the general population, but might to some extent provide new evidence on joint effects of air pollution and physical activity among healthy young adults, and imply the potential impact in vulnerable populations. Second, we did not perform a formal sample size calculation before the study began due to a lack of available knowledge and prior information on this topic, but we still managed to achieve some significant results, which can shed light on power calculation in further studies. Third, due to limited sample size, we did not explore modification effect by gender and age. Finally, the MVPA value measured in our study is somewhat larger than the minimal standard recommended by WHO. This may be because subjects worn accelerometers on the wrist instead of waist and hip: when they did some wrist activities (e.g., typing), accelerometers also recorded it as physical activities, resulting in relatively higher values of MVPA (Table S5). But we believe this will not change our results, since we focused on the relative change associations in variables, not the absolute amount; in our study, we adopted longitudinal measurements and mixed-effect models to control for inter-person variation, which eliminated the influence of inflated MVPA measurement. Also, ActiGraph accelerometer (model wGT3X-BT, USA) has been verified reliability in many previous studies (Aadland and Ylvisåker, 2015; Lee et al., 2015), and physical activity value recorded on wrist is indeed higher than that worn on waist (Nakajima et al., 2008). However, as subjects should take accelerometers for 4 one-week-long sessions, it is more reasonable and convenient for them to wear accelerometers on wrist.

This study also has several strengths. To the best of our knowledge, this is the first study to investigate the separate and joint effects of short-term individual-level exposure to $PM_{2.5}$ and MVPA on cognitive function. This study also uses EEG data to explore the underlying neurological mechanism and finds beta-3 wave to be a vital mediator. Unlike other cross-sectional studies, this study uses a mixed-effect model with random individual effects to control for inter-person variation and thus obtains more robust correlation inferences of variables. More importantly, our study provides evidence on whether and how to take physical activity when air quality is bad. Although air pollution level has declined profoundly in China, air pollution levels in several cities are still beyond the WHO recommended standard. Our study suggests staying

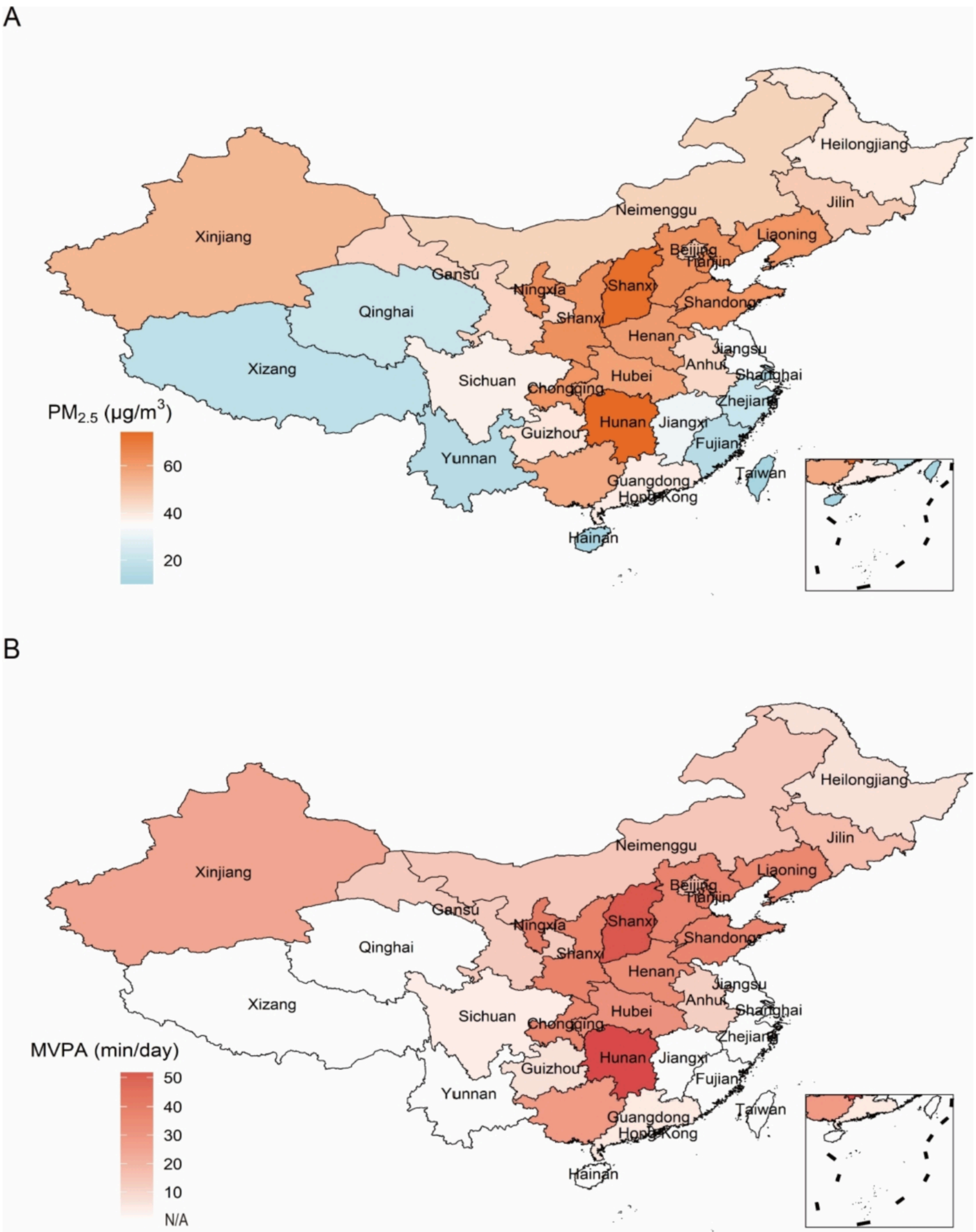

Fig. 6. Averaged $PM_{2.5}$ distribution of China in year 2020 (subgraph A) and recommended MVPA doses for residents in different provinces (subgraph B). MVPA, moderate-to-vigorous physical activity. Annual $PM_{2.5}$ exposure data of subgraph A was downloaded from Tracking Air Pollution in China database (TAP, http://tapdata.org.cn/) (Wei et al., 2021) and processed with raster package of R software, version 3.6.3. Annual $PM_{2.5}$ exposure was averaged on the basis of daily $PM_{2.5}$ concentration. The daily amount of extra MVPA recommended in subgraph B is obtained by multiplying the difference between the annual $PM_{2.5}$ exposure of each province in 2020 and the annual exposure standard (35 μg/m^3) set by the Chinese government by 1.36 min. For example, the average exposure of $PM_{2.5}$ in Beijing in year 2020 is 48.93 μg/m^3, so the recommended additional MVPA every day is 18.95 min (Calculation formula: (48.93–35) × 1.36 = 18.95). In subgraph A, the red color of regions indicates more air pollution, and the blue color of regions indicates less air pollution. In subgraph B, data in white regions is N/A, indicating that the annual $PM_{2.5}$ exposure in the corresponding region did not exceed the annual exposure standard (35 μg/m^3) established by China. Thus, no extra MVPA is needed.

sedentarily is not a good strategy to avoid the health damage of air pollution; taking physical activity is still recommended, even if in polluted days. This is the take-home message of our study.

5. Conclusion

In summary, when taken together, short-term cognitive function of healthy individuals can be directly and indirectly influenced by both MVPA and $PM_{2.5}$ in everyday life, whereby higher frequency beta-3 wave plays as a mediating role. Moreover, keeping physically active rather than staying sedentarily is still recommended to those who live in mild-to-moderate polluted environment. For every 10 μg/m^3 increase in daily $PM_{2.5}$, extra 13.6 min/day MVPA are recommended to counterbalance it.

CRediT authorship contribution statement

Yao Zhang: Conceptualization, Data curation, Formal analysis, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Limei Ke:** Data curation, Formal analysis, Project administration, Visualization, Writing – review & editing. **Yingyao Fu:** Data curation, Writing – review & editing. **Qian Di:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Xindong Ma:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics approval

The Institutional Review Board of Tsinghua University (ID number: 20190091) approved this research.

Participants' consent for publication

Consent form was obtained from every participant in our study. Detailed information about this study was posted to participants. Participants were asked to read all study information and give written informed consent before starting the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.107070.

References

Aadland, E., Ylvisåker, E., López Lluch, G., 2015. Reliability of the actigraph GT3X+ accelerometer in adults under free-living conditions. PLoS ONE 10 (8), e0134606. https://doi.org/10.1371/journal.pone.0134606.

Aguiar, A.S., Castro, A.A., Moreira, E.L., Glaser, V., Santos, A.R.S., Tasca, C.I., Latini, A., Prediger, R.D.S., 2011. Short bouts of mild-intensity physical exercise improve spatial learning and memory in aging rats: Involvement of hippocampal plasticity via AKT, CREB and BDNF signaling. Mech. Ageing Dev. 132 (11-12), 560–567. https://doi.org/10.1016/j.mad.2011.09.005.

Allegretti, A.S., Thadhani, R.I., 2018. Chronic disease, cancer, and exercise — a common link. Nat. Rev. Nephrol. 14 (5), 288–290. https://doi.org/10.1038/nrneph.2018.24.

Aly, M., Kojima, H., 2020. Acute moderate-intensity exercise generally enhances neural resources related to perceptual and cognitive processes: A randomized controlled ERP study. Mental Health Phys. Activity 19, 100363. https://doi.org/10.1016/j.mhpa.2020.100363.

An, R., Kang, H., Cao, L., Xiang, X., 2020. Engagement in outdoor physical activity under ambient fine particulate matter pollution: A risk-benefit analysis. J. Sport Health Sci. S2095254620301277 https://doi.org/10.1016/j.jshs.2020.09.008.

Avila-Palencia, I., Laeremans, M., Hoffmann, B., Anaya-Boig, E., Carrasco-Turigas, G., Cole-Hunter, T., de Nazelle, A., Dons, E., Götschi, T., Int Panis, L., Orjuela, J.P., Standaert, A., Nieuwenhuijsen, M.J., 2019. Effects of physical activity and air pollution on blood pressure. Environ. Res. 173, 387–396. https://doi.org/10.1016/j.envres.2019.03.032.

Barha, C.K., Galea, L.A., Nagamatsu, L.S., Erickson, K.I., Liu-Ambrose, T., 2017. Personalising exercise recommendations for brain health: considerations and future directions. Br. J. Sports Med. 51 (8), 636–639. https://doi.org/10.1136/bjsports-2016-096710.

Block, M.L., Calderón-Garcidueñas, L., 2009. Air pollution: mechanisms of neuroinflammation and CNS disease. Trends Neurosci. 32 (9), 506–516. https://doi.org/10.1016/j.tins.2009.05.009.

Bos, I., De Boever, P., Emmerechts, J., Buekers, J., Vanoirbeek, J., Meeusen, R., Van Poppel, M., Nemery, B., Nawrot, T., Panis, L.I., 2012a. Changed gene expression in brains of mice exposed to traffic in a highway tunnel. Inhalation Toxicol. 24 (10), 676–686. https://doi.org/10.3109/08958378.2012.714004.

Bos, I., De Boever, P., Int Panis, L., Meeusen, R., 2014. Physical activity, air pollution and the brain. Sports Med. 44 (11), 1505–1518. https://doi.org/10.1007/s40279-014-0222-6.

Bos, I., De Boever, P., Int Panis, L., Sarre, S., Meeusen, R., 2012b. Negative effects of ultrafine particle exposure during forced exercise on the expression of Brain-Derived Neurotrophic Factor in the hippocampus of rats. Neuroscience 223, 131–139. https://doi.org/10.1016/j.neuroscience.2012.07.057.

Bos, I., De Boever, P., Vanparijs, J., Pattyn, N., Panis, L.I., Meeusen, R., 2013. Subclinical effects of aerobic training in urban environment. Med. Sci. Sports Exerc. 45, 439–447. https://doi.org/10.1249/MSS.0b013e31827767fc.

Bowe, B., Xie, Y., Li, T., Yan, Y., Xian, H., Al-Aly, Z., 2018. The 2016 global and national burden of diabetes mellitus attributable to PM 2·5 air pollution. The Lancet Planetary Health 2 (7), e301–e312. https://doi.org/10.1016/S2542-5196(18)30140-2.

Burdette, 2010. Using network science to evaluate exercise-associated brain changes in older adults. Fronti. Ag. Neurosci. doi: 10.3389/fnagi.2010.00023.

Calverley, T.A., Ogoh, S., Marley, C.J., Steggall, M., Marchi, N., Brassard, P., Lucas, S.J.E., Cotter, J.D., Roig, M., Ainslie, P.N., Wisløff, U., Bailey, D.M., 2020. HIITing the brain with exercise: mechanisms, consequences and practical recommendations. J. Physiol. 598 (13), 2513–2530. https://doi.org/10.1113/JP275021.

Chang, Y.-K., Chu, C.-H., Wang, C.-C., Wang, Y.-C., Song, T.-F., Tsai, C.-L., Etnier, J.L., 2015. Dose-response relation between exercise duration and cognition. Med. Sci. Sports Exerc. 47, 159–165. https://doi.org/10.1249/MSS.0000000000000383.

Chekroud, S.R., Gueorguieva, R., Zheutlin, A.B., Paulus, M., Krumholz, H.M., Krystal, J.H., Chekroud, A.M., 2018. Association between physical exercise and mental health in 1·2 million individuals in the USA between 2011 and 2015: a cross-sectional study. The Lancet Psychiatry 5 (9), 739–746. https://doi.org/10.1016/S2215-0366(18)30227-X.

Chen, J.-C., Schwartz, J., 2009. Neurobehavioral effects of ambient air pollution on cognitive performance in US adults. NeuroToxicology 30 (2), 231–239. https://doi.org/10.1016/j.neuro.2008.12.011.

Coelho, F.G.d.M., Gobbi, S., Andreatto, C.A.A., Corazza, D.I., Pedroso, R.V., Santos-Galduróz, R.F., 2013. Physical exercise modulates peripheral levels of brain-derived neurotrophic factor (BDNF): A systematic review of experimental studies in the elderly. Arch. Gerontol. Geriatr. 56 (1), 10–15. https://doi.org/10.1016/j.archger.2012.06.003.

Cole-Hunter, T., Weichenthal, S., Kubesch, N., Foraster, M., Carrasco-Turigas, G., Bouso, L., Martínez, D., Westerdahl, D., de Nazelle, A., Nieuwenhuijsen, M., 2016. Impact of traffic-related air pollution on acute changes in cardiac autonomic modulation during rest and physical activity: a cross-over study. J. Expo Sci. Environ. Epidemiol. 26 (2), 133–140. https://doi.org/10.1038/jes.2015.66.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134 (1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.

Diaz, K.M., Shimbo, D., 2013. Physical activity and the prevention of hypertension. Curr. Hypertens. Rep. 15 (6), 659–668. https://doi.org/10.1007/s11906-013-0386-8.

Febbraio, M.A., 2017. Health benefits of exercise — more than meets the eye! Nat. Rev. Endocrinol. 13 (2), 72–74. https://doi.org/10.1038/nrendo.2016.218.

Ferree, T.C., Luu, P., Russell, G.S., Tucker, D.M., 2001. Scalp electrode impedance, infection risk, and EEG data quality. Clin. Neurophysiol. 112 (3), 536–544. https://doi.org/10.1016/S1388-2457(00)00533-2.

Freedson, P.S., Melanson, E., Sirard, J., 1998. Calibration of the computer science and applications. Inc. accelerometer. Med. Sci. Sports Exerc. 30, 777–781. https://doi.org/10.1097/00005768-199705001-00256.

Fuertes, E., Markevych, I., Jarvis, D., Vienneau, D., de Hoogh, K., Antó, J.M., Bowatte, G., Bono, R., Corsico, A.G., Emtner, M., Gislason, T., Gullón, J.A., Heinrich, J., Henderson, J., Holm, M., Johannessen, A., Leynaert, B., Marcon, A., Marchetti, P., Moratalla, J.M., Pascual, S., Probst-Hensch, N., Sánchez-Ramos, J.L., Siroux, V., Sommar, J., Weyler, J., Kuenzli, N., Jacquemin, B., Garcia-Aymerich, J., 2018. Residential air pollution does not modify the positive association between physical activity and lung function in current smokers in the ECRHS study. Environ. Int. 120, 364–372. https://doi.org/10.1016/j.envint.2018.07.032.

Gatto, N.M., Henderson, V.W., Hodis, H.N., St. John, J.A., Lurmann, F., Chen, J.-C., Mack, W.J., 2014. Components of air pollution and cognitive function in middle-aged and older adults in Los Angeles. NeuroToxicology 40, 1–7. https://doi.org/10.1016/j.neuro.2013.09.004.

Giallouros, G., Kouis, P., Papatheodorou, S.I., Woodcock, J., Tainio, M., 2020. The long-term impact of restricting cycling and walking during high air pollution days on all-cause mortality: Health impact Assessment study. Environ. Int. 140, 105679. https://doi.org/10.1016/j.envint.2020.105679.

Gopinath, B., Kifley, A., Flood, V.M., Mitchell, P., 2018. Physical activity as a determinant of successful aging over ten years. Sci. Rep. 8, 10522. https://doi.org/10.1038/s41598-018-28526-3.

Gramkow, M.H., Hasselbalch, S.G., Waldemar, G., Frederiksen, K.S., 2020. Resting state EEG in exercise intervention studies: a systematic review of effects and methods. Front. Hum. Neurosci. 14, 155. https://doi.org/10.3389/fnhum.2020.00155.

Henz, D., Schöllhorn, W.I., 2017. EEG brain activity in dynamic health qigong training: same effects for mental practice and physical training? Front. Psychol. 8 https://doi.org/10.3389/fpsyg.2017.00154.

Hillman, C.H., Erickson, K.I., Kramer, A.F., 2008. Be smart, exercise your heart: exercise effects on brain and cognition. Nat. Rev. Neurosci. 9 (1), 58–65. https://doi.org/10.1038/nrn2298.

Hötting, K., Röder, B., 2013. Beneficial effects of physical exercise on neuroplasticity and cognition. Neurosci. Biobehav. Rev. 37 (9), 2243–2257. https://doi.org/10.1016/j.neubiorev.2013.04.005.

Hou, J., Liu, X., Tu, R., Dong, X., Zhai, Z., Mao, Z., Huo, W., Chen, G., Xiang, H., Guo, Y., Li, S., Wang, C., 2020. Long-term exposure to ambient air pollution attenuated the association of physical activity with metabolic syndrome in rural Chinese adults: A cross-sectional study. Environ. Int. 136, 105459. https://doi.org/10.1016/j.envint.2020.105459.

Hsieh, S.-S., Huang, C.-J., Wu, C.-T., Chang, Y.-K., Hung, T.-M., 2018. Acute exercise facilitates the N450 inhibition marker and P3 attention marker during stroop test in young and older adults. JCM 7, 391. https://doi.org/10.3390/jcm7110391.

Hwang, J., Brothers, R.M., Castelli, D.M., Glowacki, E.M., Chen, Y.T., Salinas, M.M., Kim, J., Jung, Y., Calvert, H.G., 2016. Acute high-intensity exercise-induced cognitive enhancement and brain-derived neurotrophic factor in young, healthy adults. Neurosci. Lett. 630, 247–253. https://doi.org/10.1016/j.neulet.2016.07.033.

Imai, K., Keele, L., Yamamoto, T., 2010. Identification, inference and sensitivity analysis for causal mediation effects. Statist. Sci. 25 https://doi.org/10.1214/10-STS321.

Int Panis, L., de Geus, B., Vandenbulcke, G., Willems, H., Degraeuwe, B., Bleux, N., Mishra, V., Thomas, I., Meeusen, R., 2010. Exposure to particulate matter in traffic: A comparison of cyclists and car passengers. Atmos. Environ. 44 (19), 2263–2270. https://doi.org/10.1016/j.atmosenv.2010.04.028.

Jang, J.-H., Kim, J., Park, G., Kim, H., Jung, E.-S., Cha, J., Kim, C., Kim, S., Lee, J.-H., Yoo, H., 2019. Beta wave enhancement neurofeedback improves cognitive functions in patients with mild cognitive impairment: A preliminary pilot study. Medicine 98, e18357. https://doi.org/10.1097/MD.0000000000018357.

Jasper, H.H., 1958. The ten–twenty electrode system of the International Federation. Electroencephalogr. Clin. Neurophysiol. 10, 370–375.

Jung, T.-P., Makeig, S., Humphries, C., Lee, T.-W., McKeown, M.J., Iragui, V., Sejnowski, T.J., 2000. Removing electroencephalographic artifacts by blind source separation. Psychophysiology 37 (2), 163–178. https://doi.org/10.1111/1469-8986.3720163.

Kan, D.P.X., Lee, P.F., 2015. Decrease alpha waves in depression: An electroencephalogram (EEG) study. In: 2015 International Conference on BioSignal Analysis, Processing and Systems (ICBAPS). Presented at the 2015 International Conference on BioSignal Analysis, Processing and Systems (ICBAPS), IEEE, Kuala Lumpur, Malaysia, pp. 156–161. doi: 10.1109/ICBAPS.2015.7292237.

Killgore, W.D.S., Olson, E.A., Weber, M., 2013. Physical exercise habits correlate with gray matter volume of the hippocampus in healthy adult humans. Sci. Rep. 3, 3457. https://doi.org/10.1038/srep03457.

Krzyzanowski, M., Cohen, A., 2008. Update of WHO air quality guidelines. Air Qual. Atmos. Health 1 (1), 7–13. https://doi.org/10.1007/s11869-008-0008-9.

Kubesch, N.J., de Nazelle, A., Westerdahl, D., Martinez, D., Carrasco-Turigas, G., Bouso, L., Guerra, S., Nieuwenhuijsen, M.J., 2015. Respiratory and inflammatory responses to short-term exposure to traffic-related air pollution with and without moderate physical activity. Occup. Environ. Med. 72 (4), 284–293. https://doi.org/10.1136/oemed-2014-102106.

Laeremans, M., Dons, E., Avila-Palencia, I., Carrasco-Turigas, G., Orjuela, J.P., Anaya, E., Cole-Hunter, T., de Nazelle, A., Nieuwenhuijsen, M., Standaert, A., Van Poppel, M., De Boever, P., Int Panis, L., 2018a. Short-term effects of physical activity, air pollution and their interaction on the cardiovascular and respiratory system. Environ. Int. 117, 82–90. https://doi.org/10.1016/j.envint.2018.04.040.

Laeremans, M., Dons, E., Avila-Palencia, I., Carrasco-Turigas, G., Orjuela-Mendoza, J.P., Anaya-Boig, E., Cole-Hunter, T., De Nazelle, A., Nieuwenhuijsen, M., Standaert, A., Van Poppel, M., De Boever, P., Int Panis, L., 2018b. Black carbon reduces the beneficial effect of physical activity on lung function. Med. Sci. Sports Exerc. 50, 1875–1881. https://doi.org/10.1249/MSS.0000000000001632.

Lardon, M.T., Polich, J., 1996. EEG changes from long-term physical exercise. Biol. Psychol. 44 (1), 19–30. https://doi.org/10.1016/S0301-0511(96)05198-8.

Laufs, H., Krakow, K., Sterzer, P., Eger, E., Beyerle, A., Salek-Haddadi, A., Kleinschmidt, A., 2003. Electroencephalographic signatures of attentional and cognitive default modes in spontaneous brain activity fluctuations at rest. Proc. Natl. Acad. Sci. 100 (19), 11053–11058. https://doi.org/10.1073/pnas.1831638100.

Lee, I.-M., Shiroma, E.J., Lobelo, F., Puska, P., Blair, S.N., Katzmarzyk, P.T., 2012. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. The Lancet 380 (9838), 219–229. https://doi.org/10.1016/S0140-6736(12)61031-9.

Lee, J.A., Williams, S.M., Brown, D.D., Laurson, K.R., 2015. Concurrent validation of the actigraph gt3x+, polar active accelerometer, omron HJ-720 and yamax digiwalker SW-701 pedometer step counts in lab-based and free-living settings. J. Sports Sci. 33 (10), 991–1000. https://doi.org/10.1080/02640414.2014.981848.

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525 (7569), 367–371. https://doi.org/10.1038/nature15371.

Lindstrom, M.J., Bates, D.M., 1988. Newton-Raphson and EM algorithms for linear mixed-effects models for repeated-measures data. J. Am. Stat. Assoc. 83 (404), 1014. https://doi.org/10.2307/2290128.

Lista, I., Sorrentino, G., 2010. Biological mechanisms of physical activity in preventing cognitive decline. Cell. Mol. Neurobiol. 30 (4), 493–503. https://doi.org/10.1007/s10571-009-9488-x.

Lucas, S.JE., Cotter, J.D., Brassard, P., Bailey, D.M., 2015. High-intensity interval exercise and cerebrovascular health: curiosity, cause, and consequence. J. Cereb. Blood Flow Metab. 35 (6), 902–911. https://doi.org/10.1038/jcbfm.2015.49.

Luke, S.G., 2017. Evaluating significance in linear mixed-effects models in R. Behav. Res. 49 (4), 1494–1502. https://doi.org/10.3758/s13428-016-0809-y.

Mekari, S., Earle, M., Martins, R., Drisdelle, S., Killen, M., Bouffard-Levasseur, V., Dupuy, O., 2020. Effect of high intensity interval training compared to continuous training on cognitive performance in young healthy adults: a pilot study. Brain Sci. 10, 81. https://doi.org/10.3390/brainsci10020081.

Nakajima, K., Tagawa, T., Motoya, T., Sasaki, K., 2008. Does Actigraph in waist pocket of trousers reflect physical activity? Ieice Technical Report Me & Bio Cybernetics 108, 113–116.

Neufer, P.D., Bamman, M., Muoio, D., Bouchard, C., Cooper, D., Goodpaster, B., Booth, F., Kohrt, W., Gerszten, R., Mattson, M., Hepple, R., Kraus, W., Reid, M., Bodine, S., Jakicic, J., Fleg, J., Williams, J., Joseph, L., Evans, M., Maruvada, P., Rodgers, M., Roary, M., Boyce, A., Drugan, J., Koenig, J., Ingraham, R., Krotoski, D., Garcia-Cazarin, M., McGowan, J., Laughlin, M., 2015. Understanding the cellular and molecular mechanisms of physical activity-induced health benefits. Cell Metab. 22 (1), 4–11. https://doi.org/10.1016/j.cmet.2015.05.011.

Onywera, V.O., 2010. Childhood obesity and physical inactivity threat in Africa: strategies for a healthy future. Glob Health Promot. 17 (2_suppl), 45–46. https://doi.org/10.1177/1757975910363937.

Peirce, J.W., 2007. PsychoPy—psychophysics software in python. J. Neurosci. Methods 162 (1-2), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017.

Peters, T.M., Moore, S.C., Xiang, Y.B., Yang, G., Shu, X.O., Ekelund, U., Ji, B.-T., Tan, Y. T., Liu, D.K., Schatzkin, A., Zheng, W., Chow, W.H., Matthews, C.E., Leitzmann, M. F., 2010. Accelerometer-measured physical activity in Chinese adults. Am. J. Prev. Med. 38 (6), 583–591. https://doi.org/10.1016/j.amepre.2010.02.012.

Posada-Quintero, H.F., Reljin, N., Bolkhovsky, J.B., Orjuela-Cañón, A.D., Chon, K.H., 2019. Brain activity correlates with cognitive performance deterioration during sleep deprivation. Front. Neurosci. 13, 1001. https://doi.org/10.3389/fnins.2019.01001.

Power, M.C., Weisskopf, M.G., Alexeeff, S.E., Coull, B.A., Spiro, A., Schwartz, J., 2011. Traffic-related air pollution and cognitive function in a cohort of older men. Environ. Health Perspect. 119 (5), 682–687. https://doi.org/10.1289/ehp.1002767.

Raichlen, D.A., Alexander, G.E., 2017. Adaptive capacity: an evolutionary neuroscience model linking exercise, cognition, and brain health. Trends Neurosci. 40 (7), 408–421. https://doi.org/10.1016/j.tins.2017.05.001.

Ranft, U., Schikowski, T., Sugiri, D., Krutmann, J., Krämer, U., 2009. Long-term exposure to traffic-related particulate matter impairs cognitive function in the elderly. Environ. Res. 109 (8), 1004–1011. https://doi.org/10.1016/j.envres.2009.08.003.

Rognmo, Ø., Moholdt, T., Bakken, H., Hole, T., Mølstad, P., Myhr, N.E., Grimsmo, J., Wisløff, U., 2012. Cardiovascular risk of high- versus moderate-intensity aerobic exercise in coronary heart disease patients. Circulation 126 (12), 1436–1440. https://doi.org/10.1161/CIRCULATIONAHA.112.123117.

Rossini, P.M., Di Iorio, R., Bentivoglio, M., Bertini, G., Ferreri, F., Gerloff, C., Ilmoniemi, R.J., Miraglia, F., Nitsche, M.A., Pestilli, F., Rosanova, M., Shirota, Y., Tesoriero, C., Ugawa, Y., Vecchio, F., Ziemann, U., Hallett, M., 2019. Methods for analysis of brain connectivity: An IFCN-sponsored review. Clin. Neurophysiol. 130 (10), 1833–1858. https://doi.org/10.1016/j.clinph.2019.06.006.

Stewart, R.A.H., Held, C., Hadziosmanovic, N., Armstrong, P.W., Cannon, C.P., Granger, C.B., Hagström, E., Hochman, J.S., Koenig, W., Lonn, E., Nicolau, J.C., Steg, P.G., Vedin, O., Wallentin, L., White, H.D., 2017. Physical activity and mortality in patients with stable coronary heart disease. J. Am. Coll. Cardiol. 70 (14), 1689–1700. https://doi.org/10.1016/j.jacc.2017.08.017.

Stubbs, B., Vancampfort, D., Smith, L., Rosenbaum, S., Schuch, F., Firth, J., 2018. Physical activity and mental health. The Lancet Psychiatry 5 (11), 873. https://doi.org/10.1016/S2215-0366(18)30343-2.

Suglia, S.F., Gryparis, A., Wright, R.O., Schwartz, J., Wright, R.J., 2007. Association of black carbon with cognition among children in a prospective birth cohort study. Am. J. Epidemiol. 167, 280–286. https://doi.org/10.1093/aje/kwm308.

Thomas, S., Reading, J., Shephard, R.J., 1992. Revision of the physical activity readiness questionnaire (PAR-Q). Can. J. Sport Sci. 17, 338–345.

Tu, R., Hou, J., Liu, X., Li, R., Dong, X., Pan, M., Mao, Z., Huo, W., Chen, G., Guo, Y., Li, S., Wang, C., 2020. Physical activity attenuated association of air pollution with estimated 10-year atherosclerotic cardiovascular disease risk in a large rural Chinese adult population: A cross-sectional study. Environ. Int. 140, 105819. https://doi.org/10.1016/j.envint.2020.105819.

van Berkel, J., Proper, K.I., van Dam, A., Boot, C.R., Bongers, P.M., van der Beek, A.J., 2013. An exploratory study of associations of physical activity with mental health and work engagement. BMC Public Health 13, 558. https://doi.org/10.1186/1471-2458-13-558.

Vaynman, S., Ying, Z., Gomez-Pinilla, F., 2004. Hippocampal BDNF mediates the efficacy of exercise on synaptic plasticity and cognition. Eur. J. Neurosci. 20 (10), 2580–2590. https://doi.org/10.1111/j.1460-9568.2004.03720.x.

Vicendese, D., Olenko, A., Dharmage, S., Tang, M., Abramson, M., Erbas, B., 2013. Modelling and predicting low count child asthma hospital readmissions using General Additive Models. OJEpi 03 (03), 125–134. https://doi.org/10.4236/ojepi.2013.33019.

Vieira, R.D.P., Toledo, A.C., Silva, L.B., Almeida, F.M., Damaceno-Rodrigues, N.R., Caldini, E.G., Santos, A.B.G., Rivero, D.H., Hizume, D.C., Lopes, F.D.T.Q.S., Olivo, C. R., Castro-Faria-Neto, H.C., Martins, M.A., Saldiva, P.H.N., Dolhnikoff, M., 2012. Anti-inflammatory effects of aerobic exercise in mice exposed to air pollution. Med. Sci. Sports Exerc. 44, 1227–1234. https://doi.org/10.1249/MSS.0b013e31824b2877.

Wei, J., Li, Z., Lyapustin, A., Sun, L., Peng, Y., Xue, W., Su, T., Cribb, M., 2021. Reconstructing 1-km-resolution high-quality PM2.5 data records from 2000 to 2018 in China: spatiotemporal variations and policy implications. Remote Sens. Environ. 252, 112136. https://doi.org/10.1016/j.rse.2020.112136.

Weichenthal, S., Hatzopoulou, M., Goldberg, M.S., 2014. Exposure to traffic-related air pollution during physical activity and acute changes in blood pressure, autonomic and micro-vascular function in women: a cross-over study. Part. Fibre Toxicol. 11, 70. https://doi.org/10.1186/s12989-014-0070-4.

West, R., Alain, C., 1999. Event-related neural activity associated with the Stroop task. Cognitive Brain Res. 8 (2), 157–164. https://doi.org/10.1016/S0926-6410(99)00017-8.

Wu, Z., Wang, Z., Hu, B., Zhang, X., Zhang, F., Wang, H., Li, F., 2020. Relationships of accelerometer-based measured objective physical activity and sedentary behaviour with cognitive function: a comparative cross-sectional study of China's elderly population. BMC Geriatr 20, 149. https://doi.org/10.1186/s12877-020-01521-y.

Xiao, Q., Chang, H.H., Geng, G., Liu, Y., 2018. An ensemble machine-learning model to predict historical $PM_{2.5}$ concentrations in china from satellite data. Environ. Sci. Technol. 52 (22), 13260–13269. https://doi.org/10.1021/acs.est.8b0291710.1021/acs.est.8b02917.s001.

Zhang, Z., Hoek, G., Chang, L.-Y., Chan, T.-C., Guo, C., Chuang, Y.C., Chan, J., Lin, C., Jiang, W.K., Guo, Y., Vermeulen, R., Yeoh, E.-K., Tam, T., Lau, A.K.H., Griffiths, S., Lao, X.Q., 2018. Particulate matter air pollution, physical activity and systemic inflammation in Taiwanese adults. Int. J. Hyg. Environ. Health 221 (1), 41–47. https://doi.org/10.1016/j.ijheh.2017.10.001.