Objectively measured the impact of air pollution on physical activity and sedentary behavior in freshmen student in Beijing, China

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Research article

Keywords: Air pollution; AQI; PM2.5, Physical activity, Sedentary behavior, Youth

Posted Date: August 14th, 2019

DOI: <https://doi.org/10.21203/rs.2.12847/v1>

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Abstract

Background: Air pollution has become a major environmental health risk factor, notably in China. Air pollution potentially has the impact of human populations' health behavior. Gaps in scientific literature remain regarding more accurately estimates the relationship between air pollution and sedentary behavior in China. The purpose of this study is to examine the effect of hourly air pollution on hourly physical activity (PA) and sedentary behavior (SB) among college students living in Beijing, China. The secondary aim was to examine such associations varied at specific time. **Methods :** Participants were recruited included 340 freshmen students from Tsinghua University. Accelerometers provided PA measures, including moderate-to-vigorous physical activity (MVPA), walking steps, energy expenditure, and sedentary time for 7 consecutive days. Corresponding air pollution data collected by Beijing Municipal Ecological Environment Bureau in the closed site in Tsinghua University were measured to include average hourly air quality index (AQI) and PM 2.5 ($\mu\text{g}/\text{m}^3$). Associations were estimated using linear individual fixed-effect regressions. **Results:** A one level increase in hourly air quality index (AQI) was associated with an reduction in one-hour physical activity by 0.083 (95% confidence interval [CI] = -0.137, -0.029) minutes of MVPA, 8.822 (95% CI = -15.028, -2.617) walking steps, 0.653 (95% CI = -1.033, -0.273) kcals of energy expenditure. A $10\mu\text{g}/\text{m}^3$ increase in air pollution concentration in hourly PM 2.5 was associated with a reduction in one-hour physical activity by 0.021 (95% confidence interval [CI] = -0.033, -0.010) minutes of MVPA, 2.232 (95% CI = -3.548, -0.916) walking steps, 0.170 (95% CI = -0.250, -0.089) kcals of energy expenditure and an increase in one-hour sedentary behavior 0.045 (0.005, 0.0845). At specific time, stronger negative associations of AQI and PM 2.5 air pollution with PA at 8 am, 4 pm, 5 pm and 7 pm. Similarly, stronger positive associations of one hour AQI and PM 2.5 air pollution with SB at 8 am, 9 am, 11 am, and 7 pm. **Conclusions:** Air pollution decrease physical activity and increases sedentary behavior among freshman students living in Beijing, China. The impact of air pollution on physical activity and sedentary behavior at a specific time was different.

Introduction

Air pollution has become a major environmental health risk factor for overall health worldwide. Air pollution levels in China have increased rapidly due to the industrialized use of fossil fuel and population growth [1]. The interaction between gases (NO_2) and particulate matter particles with a diameter of less than $2.5\text{ }\mu\text{m}$ ($\text{PM}_{2.5}$) or less than $10\text{ }\mu\text{m}$ (PM_{10}) results in air pollution [2]. The irritating photochemical cocktail known as smog is formed when particulate matter components and gases combine with ozone following sunlight exposure [2]. Previous evidences has showed that exposure to air pollution has been detrimental to various health outcomes e.g., cardiovascular disease, stroke, lung cancer, respiratory disease, all-cause mortality, sleep Apnea, depression [3-8]. Air pollution has been a major public health issue in many rapid developing industrialization counties. China and India are two of the world's largest developing economies that have prioritized minimizing its populations' exposure to air pollution [9, 10] . Elevated levels of air pollution in China have increased the risk for health problems such as elevated blood pressure, myocardial infarction and stroke, and respiratory diseases such as asthma and bronchitis [3, 5-7]. Moreover, a recent study reported that air pollution in China lead to reduce life expectancy by 3.1 years [11]. In 2010, 4.2 million deaths worldwide and 1.2 million deaths in China may have occurred due to ambient air pollution [12, 13].

Strong evidence indicates engaging in regular physical activity (PA) has many health benefits including increased effective weight management, reduced risk of all-cause mortality, and prevention and management of chronic diseases, e.g., cardiovascular diseases, diabetes, colon and breast cancer, hypertension, coronary heart disease, osteoarthritis[14-16]. To maintain a healthy weight and prevent obesity, the recommended guidelines by the U.S. Department of Health and Human Services for time spent in moderate to vigorous physical activity for youth is ≥ 60

minutes per day[14] . Despite this, a large number of young adults worldwide are physical inactivity. It is estimated that a large proportion of Chinese adolescents do not maintain the recommended guidelines for moderate to vigorous physical activity [17]. While there are several health benefits to physical activity, performing physical activity under high levels of air pollution may accelerate the risks for adverse health effects such as asthma attacks and heart or lung pathologies [18-20] . Outdoor parks and playgrounds are common places to perform physical activity in China [21], and the presence of air pollution in China may further discourage young adults from engaging in regular physical activity and exercise [22].

Sedentary behavior (SB) is defined as any sitting, reclining or lying behavior that maintains a low energy expenditure (≤ 1.5 metabolic equivalents [METs]) [23]. Previous studies reported that youth and adults spend on average 6-8 hours per day in SB [24, 25]. Independent of PA, prolonged SB has found to lead to negative health outcomes, including increased risk of obesity, type 2 diabetes, cardiovascular diseases and all-cause mortality among adolescents and adults [23, 26-29].

Substantial research has measured the effects of air pollution on health outcomes, but few studies have determined its impact on health-related behaviors, specifically PA and SB behavior. There are three major gaps in scientific literature and the need for further investigation. First, existing research on the associations between air pollution, PA and SB are limited. A systematic review located eight studies examining the negative correlation between air pollution and physical activity [30]. Six out of the eight studies came from the U.S.[31-35] , one from the UK [36] , and one from Mexico [37]. Three population-based studies in the U.S. have analyzed the impact of air pollution on physical activity [32, 33, 38]. However, air pollution levels in China are tenfold higher than in the U.S., thus existing research on air quality impact may not be comparable in China. To our knowledge, there are only three cohort-based studies in China that have reported air pollution impact on college students [22, 39] and university retiree [40]. There are only three previous studies regarding the impact of air pollution on SB on college students[41] and adults [42, 43].

Second, most previous studies used a self-reported survey method, therefore, existing studies were subject to social desirability bias and limited by the frequency of physical activity performance and SB data (i.e., week by week, month by month, or year by year). This study is the first to provide precise, objectively measured data by using of the digital accelerometer to measure PA and SB among university freshman students in China. A digital accelerometer omits the chance for social desirability bias while providing minute-by-minute measurements of PA and SB. Third, to date, all previous studies estimated the impact on health-related behaviors week by week, month by month, or year by year, no study investigate the relationship between air pollution and PA and SB at a specific time.

This study reported the associations between air pollution, physical activity and sedentary behavior among university freshman students living in Beijing, China. Objectively measured data were collected by using of the digital accelerometers during this study. The final sample size was 340 participants. Hourly air pollution data and minute-by-minute physical activity and sedentary behavior data were measured. We hypothesized that in response to high levels of air pollution, university freshmen reduced their physical activity behaviors and increased their sedentary behavior. We also hypothesized that such associations varied at a specific time.

Methods

Participants

All participants in the study were freshman students enrolled at the 2017 freshmen Tsinghua University in Beijing, China from November 2017 to April 2018. Participants were recruited in a physical education class. When Beijing air quality forecast 2-3 days air pollution is coming in future 7 days in advance, we recruited the participants in the physical education class. A physical education teacher asked to participants if they were willing to wear an accelerometer for one week and complete a questionnaire. Upon acceptance, the participant was invited to Lab of science in exercise and health of Tsinghua University to complete a survey and wear an accelerometer. Each participant completed one paper-pencil based health survey on demographic status (age, gender, ethnicity, lifestyle smoking, drinking, mental and physical health conditions). Body mass index (BMI) was determined from measured height and weight. Participants was recruited 6 times during the study period (Nov 6-14, 2017; Nov 15-30, 2017; Dec 18, 2017-Jan 5, 2018; Feb 27- Mar 6, 2018; Mar 12- Mar 19, 2018; Mar 26-Apr 3, 2018). Of 344 participants who consented to wear an accelerometer, 4 participants' data was exclusion for 2 devices error, 2 accelerometer missing and failure to return the device. All participants gave informed consent, and were approved by the Tsinghua University Institutional Review Board (IRB #2017DX02_11).

PA and SB measurement

Participant wore an Actigraphy (wGT3X-BT) accelerometer over the right hip on a waist band in the Lab of science in exercise and health in Tsinghua University. Participants were instructed to put on the accelerometer after waking up each morning and take it off before going to bed each night. Participants were instructed to wear the accelerometer at least 10 hours per day, and to remove it only during showers, bathing, swimming or other water activity in the daytime. Participants were instructed to wear the device for 7 continuous days and return the device immediately after filling out a survey in the same lab. The recording epoch was set to record by one minute. Hourly physical activity and sedentary behavior were summed using the minutes' data. For all participants, absolute time spent in sedentary behavior, moderate-to-vigorous (MVPA), walking steps, kcals in energy expenditure were estimated. Nonwear hour periods were defined as 60 consecutive minutes of zero activity intensity count at 1 METs and 0 kcals in one hour [44].

Environmental measures

Air pollution data and other environmental measures were selected including—air quality index (AQI), PM_{2.5}, average daytime temperature (C). Hourly AQI and PM_{2.5} data were provided by Beijing Municipal Ecological Environment Bureau. The data collection site is Wan Liu of the Hai Dian district site, which is around 5 KM from Tsinghua University. Daytime temperature was retrieved from the China Meteorological Administration.

Statistical Analyses

Descriptive statistics were computed including means, SD, and percentages and compared characteristics of the overall sample. Chi-square tests were conducted to compare categorical variables. ANOVA tests and t-test were used to compare for continuous variables. One-way repeated measures ANOVA tests were conducted to compare the differences in hourly time between 7 am- 11 pm. Adjusted linear individual fixed-effect regressions were performed revealed the associations between the accelerometer data and air pollution from the participant when controlling for age, sex, race, BMI, smoking, drinking, temperature, rain of days.

The key independent variables were AQI and PM_{2.5} during this time. We performed 6 levels (1-6) in AQI and 10µg/m³ in PM_{2.5} in the model analysis. Individual-level time-variant covariates and environmental measures including

average daytime temperature were controlled for the aforementioned. After that, each outcome variable was analyzed using separate regression and stratified by specific time (from 7 am to 11 pm).

Compared to the conventional pooled cross-sectional regression, individual fixed-effect regression was selected because it only used within-individual variations in hourly physical activity and sedentary behavior to identify the impacts of air pollution concentration, thus removing potential omitted variable bias due to differences in time-invariant individual characteristics such as habits, and personal preferences.

Results

The Characteristics of Survey Participants.

Table 1 presents the characteristics of the participants. Participants were 340 freshmen. Among the 340 participants, accounting for more than two third (70.58%) were male. Participants were compliant wearing GT3X accelerometer 42291 hours over 7 continuous days. The mean age of the participants was 18.33 (SD = 1.02). The mean participant's BMI was 21.61 kg/m² (SD = 3.07), male were significantly higher than female ($P < 0.001$). Only 0.88% of participants were reported smoker and 2.93% was reported drinkers. The mean self-rated physiological health scores were 5.54 (SD = 1.78) and the mean self-rated mental health scores were 6.51 (SD = 1.88).

The Air Pollution Variations.

Table 2 shows the variations of air pollution measures during the study period. The mean AQI value at one-hour was 106.08 (SD = 88.66). There were 10,977 (26.63%), 14,980 (36.35%), 6,476 (15.71%), 2,329 (5.65%), 4,868 (11.81%) and 1,583 (3.84%) one hour AQI at "good" AQI (0-50), "moderate" AQI (51-100), "Unhealthy for sensitive groups" AQI (101-150), "unhealth" AQI (151-200), "very unhealthy" AQI (201-300) and "Harzardous" AQI (>300), respectively. The mean concentration of PM_{2.5} value at one-hour was 68.02 µg/m³ (SD = 66.77). A majority proportion (59.11%) of average PM_{2.5} were in concentrations exceeding the U.S. Environmental Protection Agency (EPA) PM_{2.5} standard of 35µg/m³.

The PA and SB Variations.

Table 3 presents the mean variations of participants' PA and SB in the study. As illustrated, there are large variations in PA and SB. For example, the mean minutes of the participant's one-hour MVPA was 3.53 (SD = 4.50). One-hour mean minutes of MVPA ranged largely from 1.64 (SD = 2.69) at 11 pm to 6.11 (SD = 8.32) at 5 pm in the participants ($P < .001$). The mean steps of the participant's one-hour walking was 394.46 (SD = 627.24). One-hour mean steps of walking ranged largely from 147.03 (SD = 302.91) at 11 pm to 709.78 (SD = 947.25) at 5 pm in the participants ($P < .001$). Similarly, the mean kcals participant's one-hour energy expenditure was 394.46 (SD = 627.24). One-hour mean steps of walking ranged largely from 9.20 (SD = 19.53) at 11 pm to 38.04 (SD = 66.19) at 5 pm in the participants ($P < .001$). Whereas the mean minutes participant's one-hour SB was 31.48 (SD = 19.69). One-hour mean minutes of SB ranged largely from 38.56 (SD = 18.16) at 11 pm to 25.44 (SD = 17.07) at 12 am in the participants ($P < .001$).

Impact of AQI on PA and SB.

Table 4 shows the estimated effects of Air quality index (AQI) on individual-level outcomes hourly PA and SB using linear individual fixed-effect regressions. AQI was found to be significantly negatively associated with one-hour PA among participants. A one level increase in AQI was linked with a significant reduction in minutes of one-hour

MVPA, in steps of one-hour walking, in kcals of one-hour energy expenditure by 0.083 (95% confidence interval [CI] = -0.137, -0.029), 8.822 (95% confidence interval [CI] = -15.028, -2.617), 0.653 (95% confidence interval [CI] = -1.033, -0.273), respectively ($P < .001$).

The impact of AQI on individual-level one-hour PA at a specific time was different. AQI was found to be higher negatively associated with participants' one-hour PA at 8 am, 4 pm, 5 pm and 7 pm. In specific, a one level increase in AQI was linked with a significantly reduction in steps of one-hour walking at 8 am, 4 pm and 7 pm by 35.345 (95% confidence interval [CI] = -59.468, -11.220), 74.738 (95% confidence interval [CI] = -108.273, -41.204), 23.516 (95% confidence interval [CI] = -45.675, -1.357), respectively. However, AQI was found to be positively associated with participants' one-hour PA at 10 am and 3 pm. There was no significant relationship between AQI and one-hour SB among participants.

Impact of PM_{2.5} on PA and SB.

Table 5 indicates the estimated effects of air pollution concentration in PM_{2.5} on individual-level outcomes hourly PA and SB using linear individual fixed-effect regressions. PM_{2.5} was found to be significant negatively associated with one-hour PA among participants. A 10 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} was associated with a significant reduction in minutes of one-hour MVPA, in steps of one-hour walking, in kcals of one-hour energy expenditure by 0.021 (95% confidence interval [CI] = -0.033, -0.010), 2.232 (95% confidence interval [CI] = -3.548, -0.916) and 0.170 (95% confidence interval [CI] = -0.250, -0.089), respectively ($P < .001$).

The impact of PM_{2.5} on individual-level one-hour PA at specific time was also different. PM_{2.5} was found to be higher negatively associated with participants' one-hour PA at 8 am, 4 pm, 5 pm and 7 pm. In specific, 10 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} was linked with a significantly reduction in steps of one-hour walking at 8 am, 4 pm, 5pm and 7 pm by 6.134 (95% confidence interval [CI] = -11.274, -0.995), 10.871 (95% confidence interval [CI] = -17.444, -4.298) and 9.654 (95% confidence interval [CI] = -17.632, -1.676) and 4.973 (95% confidence interval [CI] = -9.588, -0.002), respectively. However, PM_{2.5} was found to be positively associated with participants' one-hour PA at 10 am, 2 pm and 3 pm. Air pollution concentration in PM_{2.5} was found to be significant positively associated with SB among participants. A 10 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} was associated with a significant increase in minutes of one-hour SB by 0.045 (95% confidence interval [CI] = -0.005, -0.0845).

The impact of PM_{2.5} on individual-level one-hour SB at specific time was also different. PM_{2.5} was found to be higher positively associated with participants' one-hour SB at 9 am, 11 pm, 5 pm and 7 pm. In specific, a 10 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} was linked with a significantly increase in minutes of one-hour SB at 9 am, 11 pm, 5pm and 7 pm by 0.247 (95% confidence interval [CI] = 0.067, 0.427), 0.342 (95% confidence interval [CI] = 0.139, 0.544), 0.192 (95% confidence interval [CI] = 0.030, 0.355) and 0.201 (95% confidence interval [CI] = 0.048, 0.355), respectively. However, PM_{2.5} was found to be negatively associated with participants' one-hour PA at 10 am and 3 pm.

Discussion

The purpose of this study was to examine the impact of air pollution level on physical activity and sedentary behavior among university freshmen students in Beijing, China from November 2017 to April 2018 using objectively-measured physical activity and sedentary behavior. Our study found a significantly negative relationship between air pollution and physical activity and a positive relationship between air pollution and sedentary behavior. With a one level increase in AQI and a 10 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5}, hourly total minutes of MVPA, walking steps and kcals of

energy expenditure was significantly reduction. A $10\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ was associated with a significantly SB increase among participants. The impact of air pollution on individual-level one-hour PA and SB behavior at a specific time was different. To our best knowledge, this is the first study to use objective methods to determine the effect of hourly air pollution on physical activity and sedentary behavior. In addition, this is the first study to estimate the impact of air pollution on physical activity and sedentary behavior at a specific time.

Our findings on the negative relationship between air pollution and physical activity are consistent with existing literature [22, 33, 40, 45, 46]. In our study, we found that one-hour AQI increase one level was associated with decreasing by 9 walking steps in one hour and a $10\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ air pollution was linked with reduction by 2 walking steps in one hour. Previous two U.S. studies linked one unit ($<10\mu\text{g}/\text{m}^3$) monthly average $\text{PM}_{2.5}$ increase of air pollution was associated with decreasing 0.46% leisure time physical activity using a cross sectional study from the US Behavioral Risk Factor Surveillance System (BRFSS) survey [32, 33]. Evidence from our previous follow-up studies also found one unit ($44.72\text{--}56.6\mu\text{g}/\text{m}^3$) $\text{PM}_{2.5}$ increase air pollution to discourage outdoor physical activity 110.67 PASE scores among and older adults in China [40] and to reduce 32.45 weekly minutes of moderate to vigorous physical activity (MVPA) among Chinese college students [22, 39]. However, these previous studies were limited by the potential social bias of self-report measures of PA and also have not been able to examine the hourly effects of air pollution on objective PA. Only two studies with objectively measured data have reported that the association between air pollution and PA. Consistent with this study, one study reported that air pollution level of AQI increase was associated with participates' reduction in outdoor PA such as running, biking, and walking based on 153 users of an exercise app in middle age adults [46]. With this current analysis, we can more precise using accelerometers to estimate the impact of AQI and $\text{PM}_{2.5}$ air pollution on MVPA, energy expenditure and steps, rather than using an exercise app associated with PA. Inconsistent with this study, another study showed that $\text{PM}_{2.5}$ increase had no impact on physical activity in Beijing of 40 Han Chinese participants in the mean age of 31 using GT3X accelerometers [47]. A possible explanation for this difference could be that 40 participants were relatively too small of a sample and the difference of the participants. Based on 340 participants' GT3X accelerometers data, we can more confidently suggest air pollution level of AQI and $\text{PM}_{2.5}$ increase was associated with reduction of PA in MVPA, energy expenditure and walking steps.

This study confirmed findings from previous studies regarding the positive correlation between air pollution and sedentary behavior [41, 42, 48]. This finding suggests that a one-hour $10\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ air pollution increase was associated with increase sedentary behavior by 0.045 minutes in one hour. Consistent with our previous research, an increase in air pollution concentration in $\text{PM}_{2.5}$ by one unit ($81.16\mu\text{g}/\text{m}^3$) was associated with an increase in total weekly hours of SB by 6.24 hours among a large sample (12,174) university freshmen in China based on a cohort study survey [41]. Interestingly, in the current study, the finding revealed that there is no significant association between AQI and SB in our participant, which is different from our previous finding from the same sample. Another recent study reports that better AQI levels were significantly associated with approximately 20 min decrease in SB, and $\text{PM}_{2.5}$ pollution were associated with approximately 45 min reduction in SB based on 3270 Chinese users of wrist-worn activity trackers data[42]. These previous studies are consistent with this results regarding the relationship between $\text{PM}_{2.5}$ and SB and inconsistent with the relationship between AQI and SB. A possible explanation for this difference could be that participants perceived more sensitive on $\text{PM}_{2.5}$ air pollution concertation than AQI air pollution concertation. Compared with AQI, $\text{PM}_{2.5}$ has stronger association with smog phenomenon. Therefore, $\text{PM}_{2.5}$ air pollution concentration increase was more likely to reduce their exposure by choosing SB behavior. In addition, contrary to this result, a recent study reported that air pollution was negatively

associated with SB among residents in Shanghai, China [43]. A possible explanation for this difference could be that the residents' SB behavior is different from our freshmen students. Moreover, self-reported SB may have potential social bias. To our knowledge, this is one of the first studies to investigate the impact of air pollution on SB by hourly use objectively measured GT3X accelerometers. Because of conflicting results in this emerging area and somewhat preliminary of this finding, additional investigations are necessary to fully explore the effect of air pollution on SB among different groups.

The impact of air pollution on individual-level PA and SB at a specific time was different. This study is the first to examine the association between air pollution and PA, SB at a specific time. Stronger negative associations of AQI and PM_{2.5} air pollution with MVPA, walking steps and energy expenditure in the morning before 8 am, in the afternoon at 4 pm, 5 pm and 7 pm. Similarly, stronger positive associations of one hour AQI and one hour PM_{2.5} air pollution with SB in the morning at 8 am, 9 am, 11 am, and in the afternoon at 7 pm. In this study, all participants were recruited from freshmen. Typically, a substantial proportion of freshmen have no class before 8 am in the morning, and/or after 4 pm. Participants in this study can choose PA or SB behavior according to their own preferences in the leisure time. Similar time-specific relationships between built environment and PA were found in the previous study [49, 50]. However, it is interesting that positive associations of AQI and PM_{2.5} air pollution with MVPA, walking steps and energy expenditure in the morning at 10 am, in the afternoon at 3 pm; negative associations of AQI and PM_{2.5} air pollution with SB. This could be explained by the fact that there are classes (including physical education class) for a substantial proportion of freshmen participant at 10 am in the morning and 3 am in the afternoon, so they had to go to class. Freshmen have to active transportation (e.g. walking or bicycling to/from class, especially PE class) or do more exercise in physical education class regardless of air pollution. Therefore, 10 am in the morning and 3 pm in the afternoon associations between air pollution and PA or SB observed in this study are logical. Thus, this study confirms that the impact of air pollution on PA and SB are different from patterns of in time-specific associations. This finding is closer to the 'true' potential effects of air pollution on PA and SB.

First, the strengths of this study reside in its objectively measured physical activity-related behavior and precise reporting of data. Most existing studies on the impact of air pollution on physical activity and sedentary behavior have used subjective methods, allowing for uncontrolled confounding bias due to self-report and limited frequency of physical activity data. Second, this is one of the first studies to measure the impact of air pollution on physical activity and sedentary behavior by one hour using objective methods. Third, this is the first study to examine time-specific results on the relationship between air pollution and objectively measured PA and SB. However, a few limitations to this study should be noted. First, using accelerometers to assess PA and SB, we can't being able to identify types of PA and SB. Second, all participants were recruited by a convenience sample. Freshman students from one university cannot represent all university students in Beijing, China or nationwide therefore limiting the generalizability of the study's findings. Future studies are warranted to produce more generalized estimates.

Conclusion

In conclusion, the present study to examine the relationship between air pollution and hourly behavioral modification to relate objectively-assessed PA and SB among university freshmen in Beijing, China. A negative association between hourly AQI and PM_{2.5} and hourly PA in minutes of MVPA, walking steps and energy expenditure among study participants was found. A positive relationship between hourly AQI and PM_{2.5} and one-hour SB modification among study participants was estimated. The impact of air pollution on individual-level PA

and SB at specific time among freshmen was different. This requires policy maker to take action to reduce levels of air pollution in China. Future studies should consider the replication of the study findings in other groups.

Abbreviations

BMI: body mass index; PA: physical activity; SB: sedentary behavior; MVPA: moderate-to-vigorous physical activity; PM_{2.5}: Particulate matter with a diameter less than 2.5 microns; AQI: air quality index

Declarations

Ethics approval and consent to participate

This study was approved by the Tsinghua University Institutional Review Board (IRB #2017DX02_11). All the participants gave written informed consent during the study.

Consent for publication

Not applicable

Availability of data and materials

The datasets generated and/or analyzed during the current study are not publicly available due to confidentiality reasons, but are available from the corresponding author on reasonable request.

Competing interests

The author declares that they have no competing interests.

Funding

This study was supported by National Social Science Foundation of China (17CTY020, 16BTY065, 15BTY073) and by The National Key Research and Development Project (2018YFF0300901, 2018YFF0300902).

Authors' contribution

Hongjun Yu and Miao Yu designed and conceived the study. Yin Wu, Shelby Paige Gordon and Jiali Cheng were involved collected physical activity and sedentary behavior data. Yin Wu, Jiali Cheng, Panpan Chen were involved air pollution and ambient temperature data. Hongjun Yu and Yangyang Wang analyzed data. Hongjun Yu and Miao Yu wrote the manuscript. All authors read and approved the final manuscript.

Acknowledgements

We are grateful for the support of all the participants in the study. We are grateful to the Beijing Municipal Ecological Environment Bureau provided the hourly AQI and PM_{2.5} data and the China Meteorological Administration provided average daytime temperature (C) data in Beijing, China.

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Tables

Table 1. The characteristics of subjects

Characteristics	Male	Female	Total	p
Gender, n (%)	240 (70.58)	100 (29.41)	340	<0.001
Compliance, hour	31331 (74.08)	10960 (25.92)	42291	<0.001
Age (yr), mean (SD)	18.33 (1.02)	18.63 (0.83)	18.42 (0.98)	0.008
Height (cm), mean (SD)	175.62 (6.01)	164.01 (5.51)	172.09 (7.93)	<0.001
Weight (kg), mean (SD)	68.16 (11.50)	55.39 (6.74)	64.32 (11.85)	<0.001
Body mass index, mean (SD)				
BMI (kg/m ²)	22.05 (3.23)	20.61 (2.41)	21.61 (3.07)	<0.001
Smoking, n (%)	3 (100.00)	0 (0)	3 (0.88)	0.001
Drinking n (%)	2 (81.87)	5 (18.53)	7 (2.93)	0.001
Self-rated physical health , mean (SD)				
Physical health score (1-10)	5.54 (1.79)	5.56 (1.75)	5.54 (1.78)	0.928
Self-rated mental health , mean (SD)				
Mental health score (1-10)	6.69 (1.91)	6.12 (1.78)	6.51 (1.88)	0.01

Table 2. Air quality index and PM2.5 categories during the study period by hours.

	Level	Alarm	Levels of health concern	Value range	N	%
AQI					41213	100
	1	Green	Good	0-50	10,977	26.63
	2	Yellow	Moderate	51-100	14,980	36.35
	3	Orange	Unhealthy for sensitive groups	101-150	6,476	15.71
	4	Red	Unhealth	151-200	2,329	5.65
	5	Purple	Very unhealthy	201-300	4,868	11.81
	6	Maroon	Harzardous	>300	1,583	3.84
PM2.5 (µg/m ³)					40947	100
	1	Green	Good	0-12	9,954	23.84
	2	Yellow	Moderate	12.1-35.4	7,121	17.05
	3	Orange	Unhealthy for sensitive groups	35.5-55.4	6,700	16.05
	4	Red	Unhealth	55.5-150.4	11,816	28.30
	5	Purple	Very unhealthy	150.5-250.4	5,205	12.47
	6	Maroon	Harzardous	>250.5	958	2.29

Table 3. Average total and specific time of physical activity, sedentary behavior

	MVPA ^a	<i>p</i>	Steps ^b	<i>p</i>	Kcals ^c	<i>p</i>	SB ^d	<i>p</i>
<i>Total average PA^e and SB</i>								
	3.53 (4.50)		394.46 (627.24)		19.83 (39.05)		31.48 (19.69)	
<i>Specific Hourly average PA and SB</i>	<0.001		<0.001		<0.001		<0.001	
7:00 am	4.64 (3.78)		504.93 (434.06)		24.39 (23.46)		34.21 (16.28)	
8:00 am	2.30 (4.11)		247.83 (421.22)		12.21 (26.2)		36.86 (19.21)	
9:00 am	4.35 (3.93)		483.16 (443.54)		22.76 (23.42)		28.85 (17.63)	
10:00 am	2.00 (4.55)		213.17 (507.82)		11.23 (30.63)		34.50 (20.39)	
11:00 am	3.72 (4.83)		433.45 (555.34)		19.22 (29.28)		29.47 (19.64)	
12:00 am	5.39 (5.33)		629.81 (589.17)		27.92 (33.95)		25.44 (17.07)	
1:00 pm	4.07 (5.21)		446.54 (574.5)		22.22 (35.53)		29.12 (18.15)	
2:00 pm	2.56 (5.48)		269.96 (557.56)		15.16 (39.02)		32.62 (20.78)	
3:00 pm	4.14 (6.44)		482.08 (767.05)		24.67 (49.65)		29.91 (20.52)	
4:00 pm	4.13 (7.42)		460.37 (823.03)		25.89 (58.54)		29.10 (20.47)	
5:00 pm	6.11 (8.32)		709.78 (974.25)		38.04 (66.19)		25.68 (19.92)	
6:00 pm	4.91 (5.71)		571.65 (645.38)		25.98 (38.33)		25.90 (17.91)	
7:00 pm	3.17 (5.02)		354.86 (569.4)		17.05 (33.59)		30.37 (19.2)	
8:00 pm	2.32 (5.06)		258.11 (574.69)		13.24 (35.02)		31.42 (19.84)	
9:00 pm	3.75 (5.77)		415.96 (663.78)		21.61 (41.93)		28.63 (19.19)	
10:00 pm	3.08 (4.74)		321.16 (588.7)		17.81 (35.3)		31.33 (18.95)	
11:00 pm	1.64 (2.69)		147.03 (302.91)		9.20 (19.53)		38.56 (18.16)	

^a Moderate-to-vigorous physical activity; ^bWalking steps in one hour; ^cEngery expenditure in kcals in one hours;
^sSedentary behavior; ^ePhysical activity.

Table 4. Estimated effects of hourly AQI on individual-level one-hour PA and SB outcomes.

Effects	MVPA		Steps		Kcals		SB	
	Coefficient	#	Coefficient	#	Coefficient	#	Coefficient	#
	(95% CI)	Observations (# participants)	(95% CI)	Observations (# participants)	(95% CI)	Observations (# participants)	(95% CI)	Observations (# participants)
<i>Total effects</i>								
	-0.083** (-0.137, -0.029)	40,275 (340)	-8.822** (-15.028, -2.617)	40,275 (340)	-0.653** (-1.033, -0.273)	40,275 (340)	-0.085 (-0.271, 0.101)	40,275 (340)
<i>Specific times effects</i>								
7:00 am	0.063 (-0.138, 0.264)	1,362 (316)	6.340 (-16.820, 29.500)	1,362 (316)	-0.182 (-0.955, 1.318)	1,362 (316)	-0.170 (-1.107, 0.767)	1,362 (316)
8:00 am	-0.397** (-0.635, -0.159)	1,750 (331)	-35.345** (-59.468, -11.220)	1,750 (331)	-2.365** (-3.897, 0.833)	1,750 (331)	1.021* (0.013, 2.028)	1,750 (331)
9:00 am	0.045 (-0.146, 0.236)	2,165 (339)	-1.185 (-22.817, 20.447)	2,165 (339)	0.925 (-0.161, 2.012)	2,165 (339)	1.134** (0.308, 1.960)	2,165 (339)
10:00 am	0.209 (-0.035, 0.453)	2,116 (338)	18.878 (-7.944, 45.700)	2,116 (338)	1.853* (0.241, 3.465)	2,116 (338)	-0.188 (-1.190, 0.814)	2,116 (338)
11:00 am	-0.128 (-0.372, 0.116)	2,266 (339)	-13.368 (-41.214, 14.477)	2,266 (339)	-0.600 (-2.059, 0.859)	2,266 (339)	1.480** (0.557, 2.403)	2,266 (339)
12:00 am	0.072 (-0.176, 0.319)	2,399 (339)	6.592 (-20.845, 34.028)	2,399 (339)	0.270 (-1.262, 1.802)	2,399 (339)	0.162 (-0.615, 0.938)	2,399 (339)
1:00 pm	-0.107 (-0.337, 0.123)	2,400 (340)	0.429 (-24.725, 25.584)	2,400 (340)	-0.502 (-2.027, 1.022)	2,400 (340)	0.620 (-0.159, 1.400)	2,400 (340)
2:00 pm	0.126 (-0.107, 0.358)	2,297 (339)	19.153 (-5.039, 43.346)	2,297 (339)	0.825 (-0.781, 2.432)	2,297 (339)	0.150 (-0.725, 1.025)	2,297 (339)

3:00 pm	0.258* (0.025, 0.491)	2,538 (340)	28.606* (0.793, 56.420)	2,538 (340)	0.810 (0.964, 2.584)	2,538 (340)	-2.510*** (-3.215, -1.806)	2,538 (340)
4:00 pm	-0.568*** (-0.869, -0.266)	2,455 (340)	-74.738*** (-108.273, -41.204)	2,455 (340)	-4.786*** (-7.133, -2.440)	2,455 (340)	-0.040 (-0.840, 0.760)	2,455 (340)
5:00 pm	-0.330* (-0.637, -0.023)	2,502 (340)	-35.716 (-71.704, 0.272)	2,502 (340)	-2.527* (-4.907, -0.146)	2,502 (340)	0.370 (-0.362, 1.102)	2,502 (340)
6:00 pm	-0.168 (-0.374, 0.038)	2,465 (339)	-18.635 (-42.090, 4.819)	2,465 (339)	-1.088 (-2.459, 0.283)	2,465 (339)	0.293 (-0.329, 0.915)	2,465 (339)
7:00 pm	-0.234* (-0.430, -0.039)	2,389 (339)	-23.516* (-45.675, -1.357)	2,389 (339)	-1.413* (-2.723, -0.103)	2,389 (339)	0.884* (0.177, 1.590)	2,389 (339)
8:00 pm	-0.078 (-0.312, 0.156)	2,262 (338)	-14.451 (-41.265, 12.363)	2,262 (338)	-1.332 (-2.967, 0.302)	2,262 (338)	0.008 (-0.817, 0.833)	2,262 (338)
9:00 pm	-0.197 (-0.430, 0.036)	2,324 (337)	-20.228 (-47.230, 6.773)	2,324 (337)	-1.649 (-3.341, 0.043)	2,324 (337)	0.148 (-0.575, 0.872)	2,324 (337)
10:00 pm	-0.067 (-0.264, 0.131)	2,163 (337)	-18.293 (-43.128, 6.542)	2,163 (337)	-0.532 (-1.985, 0.921)	2,163 (337)	-0.068 (-0.845, 0.709)	2,163 (337)
11:00 pm	0.045 (-0.085, 0.175)	1,768 (331)	5.857 (-8.958, 20.672)	1,768 (331)	0.673 (-0.281, 1.627)	1,768 (331)	-0.059 (-0.889, 0.770)	1,768 (331)

Notes: Separate individual fixed-effect regressions were performed to estimate the effects of hourly air pollution concentrations on samples stratified by specific time. Models adjust for all time-variant individual characteristics listed in Table 1 (i.e., age, BMI, smoking status, drinking status, self-rated physical health, and self-rated mental health) and environmental variables (average temperature). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Table 5. Estimated effects of hourly PM_{2.5} on individual-level one-hour PA and SB outcomes.

Effects	MVPA		Steps		Kcals		SB	
	Coefficient	#	Coefficient	#	Coefficient	#	Coefficient	#
	(95% CI)	Observations (# participants)	(95% CI)	Observations (# participants)	(95% CI)	Observations (# participants)	(95% CI)	Observations (# participants)
<i>Total effects</i>								
	-0.021*** (-0.033, -0.010)	40,009 (340)	-2.232** (-3.548, -0.916)	40,009 (340)	-0.170*** (-0.250, -0.089)	40,009 (340)	0.045* (0.005, 0.0845)	40,009 (340)
<i>Times effects</i>								
7:00 am	0.037 (-0.010, 0.084)	1,362 (316)	4.910 (-0.500, 10.320)	1,362 (316)	0.168 (-0.097, 0.434)	1,362 (316)	-0.073 (-0.292, 0.146)	1,362 (316)
8:00 am	-0.069** (-0.120, -0.019)	1,750 (331)	-6.134* (-11.274, -0.995)	1,750 (331)	-0.397* (-0.723, -0.070)	1,750 (331)	0.154 (-0.061, 0.369)	1,750 (331)
9:00 am	-0.005 (-0.047, 0.036)	2,165 (339)	-1.792 (-6.507, 2.924)	2,165 (339)	0.079 (-0.158, 0.316)	2,165 (339)	0.247** (0.067, 0.427)	2,165 (339)
10:00 am	0.101*** (0.047, 0.155)	2,116 (338)	9.522** (3.560, 15.484)	2,116 (338)	0.786*** (0.428, 1.144)	2,116 (338)	-0.133 (-0.356, 0.090)	2,116 (338)
11:00 am	-0.029 (-0.083, 0.024)	2,216 (339)	-4.876 (-10.972, 1.220)	2,216 (339)	-0.137 (-0.458, 0.185)	2,216 (339)	0.342** (0.139, 0.544)	2,216 (339)
12:00 am	-0.004 (-0.056, 0.047)	2,390 (339)	0.046 (-5.698, 5.791)	2,390 (339)	-0.025 (-0.345, 0.295)	2,390 (339)	0.072 (-0.091, 0.234)	2,390 (339)
1:00 pm	-0.019 (-0.068, 0.030)	2,400 (339)	0.456 (-4.900, 5.811)	2,400 (339)	-0.079 (-0.403, 0.246)	2,400 (339)	0.131 (-0.035, 0.297)	2,400 (339)
2:00 pm	0.039 (-0.013, 0.091)	2,297 (339)	5.331 (-0.046, 10.708)	2,297 (339)	0.286 (-0.071, 0.643)	2,297 (339)	0.116 (-0.078, 0.311)	2,297 (339)

3:00 pm	0.052* (0.002, 0.102)	2,538 (340)	5.608 (-0.382, 11.598)	2,538 (340)	0.165 (-0.216, 0.547)	2,538 (340)	-0.455*** (-0.608, -0.303)	2,538 (340)
4:00 pm	-0.094** (-0.153, -0.034)	2,400 (340)	-10.871** (-17.444, -4.298)	2,400 (340)	-0.781** (-1.242, -0.320)	2,400 (340)	0.037 (-0.129, 0.203)	2,400 (340)
5:00 pm	-0.082* (-0.151, -0.014)	2,502 (340)	-9.654* (-17.632, -1.676)	2,502 (340)	-0.690* (-1.218, -0.162)	2,502 (340)	0.192* (0.030, 0.355)	2,502 (340)
6:00 pm	-0.033 (-0.079, 0.013)	2,465 (339)	-3.822 (-9.113, 1.470)	2,465 (339)	-0.263 (-0.572, 0.046)	2,465 (339)	0.090 (-0.050, 0.230)	2,465 (339)
7:00 pm	-0.049* (-0.092, -0.007)	2,340 (339)	-4.793* (-9.588, 0.002)	2,340 (339)	-0.291* (-0.574, -0.008)	2,340 (339)	0.201* (0.048, 0.355)	2,340 (339)
8:00 pm	-0.027 (-0.069, 0.015)	2,212 (338)	-2.978 (-7.888, 1.931)	2,212 (338)	-0.289 (-0.579, 0.000)	2,212 (338)	0.024 (-0.130, 0.179)	2,212 (338)
9:00 pm	-0.020 (-0.065, 0.025)	2,271 (337)	-0.431 (-5.609, 4.746)	2,271 (337)	-0.222 (-0.549, -0.105)	2,271 (337)	-0.003 (-0.144, 0.139)	2,271 (337)
10:00 pm	-0.007 (-0.045, 0.030)	2,163 (337)	-2.250 (-6.971, 2.472)	2,163 (337)	-0.087 (-0.363, 0.190)	2,163 (337)	0.047 (-0.101, 0.194)	2,163 (337)
11:00 pm	0.016 (-0.010, 0.042)	1,768 (331)	1.895 (-1.063, 4.853)	1,768 (331)	0.174 (-0.017, 0.364)	1,768 (331)	-0.045 (-0.211, 0.121)	1,768 (331)

Notes: Separate individual fixed-effect regressions were performed to estimate the effects of air pollution concentrations on samples stratified by specific time. Models adjust for all time-variant individual characteristics listed in Table 1 (i.e., age, BMI, smoking status, drinking status, self-rated physical health, and self-rated mental health) and environmental variables (average temperature). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.