Impact of Ambient Air Pollution on Physical Activity and Sedentary Behavior in China: A Systematic Review

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Abstract

This study systematically reviewed scientific evidence linking ambient air pollution to physical activity and sedentary behavior in China. A keyword and reference search was conducted in PubMed, Web of Science, and the Cochrane Library. Predetermined selection criteria included—study designs: interventions or experiments, retrospective or prospective cohort studies, cross-sectional studies, and case-control studies; subjects: people of all ages; exposures: specific air pollutants and/or overall air quality; outcomes: physical activity and/or sedentary behavior; and country/area: mainland China. Ten studies met the selection criteria and were included in the review. Six adopted a cross-sectional design and the remaining four adopted a prospective cohort design. Four studies assessed a specific air pollutant namely particulate matter with diameter < 2.5 μg/m^3 ($PM_{2.5}$), whereas the remaining six focused on overall air quality, defined using air quality indexes. Decline in overall air quality and increase in $PM_{2.5}$ concentration were found to be associated with reduced daily/weekly duration of outdoor leisure-time and/or transportation-related physical activity such as walking but increased duration of daytime/nighttime sleeping among Chinese residents. In contrast, evidence linking overall air quality and $PM_{2.5}$ concentration to sedentary behavior remains mixed and inconclusive. In conclusion, preliminary evidence indicates that ambient air pollution impacts Chinese residents' daily physical activity-related behaviors. Future studies adopting objective measures of physical activity and a longitudinal or experimental study design are warranted to examine the impact of air pollution on sensitive subpopulations such as children, older adults and people with pre-existing conditions, and in locations outside China.

Keywords: Air quality; Air pollutant; Physical activity; Exercise; China; Literature review

Introduction

Although the adverse effects of ambient or outdoor air pollution on health have been extensively documented (World Health Orginaization 2018), much less is known regarding its impact on local residents' health behaviors, including physical activity, sedentary behavior, and sleeping. Increasing numbers of children and adults in both high-income and low- and middle-income countries (LMICs) fall short of the guidelines-recommended physical activity levels (Li 2016; Muntner et al. 2005). Physical inactivity is a leading risk factor for morbidity and mortality worldwide (Arsenault et al. 2010; Kruk 2014; Lee et al. 2012). Sedentary behaviour refers to any waking behavior characterized by low energy expenditure while in a sitting, reclining or lying posture; long sedentary time has been found to adversely impact cardio-metabolic health (der Ploeg and Hillsdon 2017). The risk of all-cause and cardiovascular mortality significantly increases when total sedentary time is longer than 6–8 hours a day and/or total television watching time is longer than 3–4 hours a day (Patterson et al. 2018). More time spent outdoors is positively associated with moderate-to-vigorous intensity physical activity, helps people meet the guidelines-recommended physical activity level, and improves cardiorespiratory fitness (Schaefer et al. 2014).

Ambient air pollution may discourage people from engaging in regular outdoor physical activity through several mechanisms. First, exposure to air pollution is linked to decreased lung function, elevated blood pressure, and other cardiovascular and respiratory symptoms (Auchincloss et al. 2008; Brook et al. 2010; Cakmak et al. 2011), resulting in impaired exercise capacity and performance (Cutrufello et al. 2011; Marr and Ely 2010; Rundell and Caviston 2008). Second, smog appearance may discourage people from engaging in outdoor activities (Roberts et al. 2014). Finally, media alerts and warnings of poor air quality may alter people’s decision on spending time outdoors and engaging in physical activity (Saberian et al. 2017; Wen et al. 2009a). For example, the Canadian government developed a risk communication tool, the Air Quality Health Index (AQHI), which uses a 10-point scale from low to high risk to deliver information regarding the health implications of air pollution to the general public (Government of Canada 2015). In high air pollution days, the AQHI recommends to “reduce or reschedule strenuous activities outdoors” in order to mitigate the health risks of air pollution (Government of Canada 2017).

A previous review systematically identified and synthesized scientific literature that examined the impact of air pollution on physical activity (An et al. 2018). Among the seven studies included in the review (An et al. 2018), six were conducted in the U.S. and one in the U.K. All U.S.-based studies adopted a cross-sectional study design (An and Xiang 2015; Hankey et al. 2012; Roberts et al. 2014; Wells et al. 2012; Wen et al. 2009a; Wen et al. 2009b), and the U.K.-based study adopted a prospective cohort design (Alahmari et al. 2015). Specific air pollutants assessed included particulate matter with diameter < 2.5 $\mu g/m^3$ ($PM_{2.5}$), particulate matter with diameter < 10 $\mu g/m^3$ (PM_{10}), ozone (O_3), and nitrogen oxides (NO_x), whereas two studies focused on overall air quality (i.e., air quality index [AQI]). All studies found that air pollution was negatively associated with physical activity and positively associated with leisure-time physical inactivity. Study participants, in particular those with respiratory disease, reported a reduction in outdoor activities in order to mitigate the detrimental impact of air pollution. The meta-analysis based on cross-sectional studies found that one unit ($\mu g/m^3$) increase in ambient $PM_{2.5}$ concentration was associated with a 10% increase in the odds of physical inactivity among U.S. adults. Air pollution was measured by fixed monitoring stations (Hankey et al. 2012; Roberts et al. 2014; Wen et al. 2009b) or personal sensors (Alahmari et al. 2015). Five studies focused on the impact of air pollution concentration on health behaviors (Alahmari et al. 2015; An and Xiang 2015; Hankey et al. 2012; Roberts et al. 2014; Wen et al. 2009b), whereas the other two focused on the communication about air pollution in relation to health behaviors (Wells et al. 2012; Wen et al. 2009a). In particular, Wen et al (2009a) reported that media air pollution alerts via radio, television, and newspaper were associated with reduced outdoor physical activity among local residents. Wells et al (2012) reported that self-perceived air quality and air quality information communicated by local media were associated with changes in physical activity level among people with respiratory diseases. The review identified a few important limitations in the existing literature, including lack of large-scale longitudinal studies, self-reported physical activity levels that were prone to measurement error and social desirability bias, and lack of studies located in the LMICs.

It should be noted that the relationship between air pollution and physical activity may be nonlinear, and air pollution could impact physical activity behavior only after passing certain threshold concentration. In the U.S., most counties have already met the national air quality standards of $PM_{2.5}$ concentration levels, with fewer than 10 out of > 3,000 counties in the U.S. not meeting the national standard of 12.0 $\mu g/m^3$ (on annual mean concentration) by 2020 (Environmental Protection Agency 2012). In sharp contrast, 365 out of the 366 major cities in China exceeded the $PM_{2.5}$ standard of 12 $\mu g/m^3$ in 2016 (Clean Air Asia 2016). The 100 most polluted cities (including many of the largest cities such as Beijing, Tianjin, and Chengdu) had annual average $PM_{2.5}$ concentration levels seven to 19 times as high as the U.S. national average (8.5 $\mu g/m^3$) in 2015 (Clean Air Asia 2016). Air pollution is estimated to cause 1.6 million deaths per year in China, roughly 17% of all deaths nationwide (Rohde and Muller 2015). Thus, results from studies based in the U.S. and U.K. may not pertain to the high pollution settings in China (An et al. 2018). In a commentary article, Li et al. (2015)

speculated that the threat of the health damage of $PM_{2.5}$ air pollution could impact the implementation of China's physical activity programs (Li et al. 2015). In particular, Li et al. (2015) posits that severe ambient air pollution (e.g., AQI ≥ 300) may require cancellation of physical education classes or sport activities for school children (Li et al. 2015). Furthermore, both the actual air pollution level and the communication around it might impede older Chinese adults from engaging in popular outdoor activities such as walking and dancing.

This study aimed to systematically identify and review literature regarding the impact of outdoor air pollution on physical activity-related behaviors in China. It also aimed to identify the limitations and gaps in this field to guide future research.

Methods

Study selection criteria

Studies that met all of the following criteria were included in the review: (1) Study designs: interventions or experiments, retrospective or prospective cohort studies, cross-sectional studies, and case-control studies; (2) Subjects: people of all ages; (3) Exposures: specific air pollutants (e.g., PM_{10}, $PM_{2.5}$, O_3, and NO_x) and overall air quality; (4) Outcomes: physical activity, sedentary behavior, and sleeping; (5) country/area: mainland China; (6) Article type: peer-reviewed publications; (7) Time window of search: from the inception of an electronic bibliographic database to August 27, 2018; and (8) Language: articles written in English.

Studies that met any of the following criteria were excluded from the review: (1) Studies that exclusively focused on indoor air pollution; (2) Articles not written in English; and (3) Letters, editorials, study/review protocols, case reports, or review articles.

Search strategy

A keyword search was performed in three electronic bibliographic databases: PubMed, Web of Science, and the Cochrane Library. The search algorithm included all possible combinations of keywords from the following two groups: (1) “air pollutant”, “air pollutants”, “air pollution”, “air quality”, “particulate matter”, “PM2.5”, “PM10”, “outdoor pollution”, and “traffic pollution”; and (2) “health behavior”, “health behaviors”, “health behaviour”, “health behaviours”, “risk behavior”, “risk behaviors”, “risk behaviour”, “risk behaviours”, “motor activity”, “motor activities”, “sport”, “sports”, “physical fitness”, “physical exertion”, “physical activity”, “physical activities”, “physical inactivity”, “sedentary behavior”, “sedentary behaviour”, “sedentary behaviors”, “sedentary behaviours”, “sedentary lifestyle”, “sedentary lifestyles”, “inactive lifestyle”, “inactive lifestyles”, “sleep”, “sleeping”, “exercise”, “exercises”, “active living”, “active lifestyle”, “active lifestyles”, “outdoor activity”, “outdoor activities”, “walk”, “walking”, “run”, “running”, “jog”, “jogging”, “bike”, “biking”, “bicycle”, “bicycling”, “cycle”, “cycling”, “stroll”, “strolling”, “active transport”, “passive transport”, “active transportation”, “passive transportation”, "active transit", "active commuting", "travel mode", "mode of travel", "physically active", "physically inactive", "sitting", "TV", "television", "computer", "video watching", "watching video", "video time", "video games", "internet use", "screen time", "screen-time", "electronic game", and "electronic games". The search algorithm in PubMed is provided in **Appendix 1**. The Medical Subject Headings (MeSH) terms "air pollution", "air pollutants", "particulate matter", "exercise", "sports", "health behavior", and "health risk behaviors" were used in the PubMed search. All keywords in PubMed were searched with the "[All fields]" tag, which are processed using Automatic Term Mapping. The search function TS=Topic was used in Web of Science, which launches a search for topic terms in the fields of title, abstract, keywords, and Keywords Plus®. Titles and abstracts of the articles identified through the keyword search were screened against the study selection criteria. Potentially relevant articles were retrieved for evaluation of the full text. Two coauthors of this review independently conducted title and abstract screening and identified potentially relevant articles. Inter-rater agreement was assessed using the Cohen's kappa (κ=0.80). Discrepancies were resolved through discussion under the participation of a third coauthor. Besides the keyword search, we also conducted hand-searching in Google Scholar.

It is important to note that we did not include any keywords and/or MeSH terms pertaining to China in the search algorithm. This substantially expanded the scope of search and increased article harvests, with the aim of comprehensively identifying relevant studies conducted in other LMICs besides China. However, no relevant study conducted in another LMIC was identified. Therefore, we decided to narrow our review scope to China-based studies on an ad hoc basis.

Data extraction and synthesis

A standardized data extraction form was used to collect the following methodological and outcome variables from each included study: author(s), year of publication, study design, sample size, age range, proportion of females, sample characteristics, statistical model, data source, air pollution/quality level, measures of health behaviors, and key results.

We summarized the common themes and findings of the included studies narratively. A meta-analysis was proved infeasible due to overlapping samples. Specifically, An and Yu (2018) and Yu et al. (2017b) provided quantitative estimates for the impact of ambient $PM_{2.5}$ concentration on vigorous physical activity; however, both studies analyzed the same sample of freshmen at Tsinghua University in Beijing. In addition, Li and Kamargianni (2017, 2018) provided quantitative estimates for the impact of air pollution on walking and bike-sharing, but they examined the same study sample in Taiyuan. No other studies provided quantitative estimates for the impact of ambient air pollution on physical activity-related behaviors focusing on the same type and measure of air pollution and behavior.

The data extraction, theme identification, and narrative summarization were independently conducted by two coauthors of this review, (BLANK) and (BLANK). Discrepancies were resolved through discussion under the participation of a third coauthor, (BLANK).

Study quality assessment

We used the National Institutes of Health's Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies to assess the quality of each included study (National Institute of Health 2018). For each criterion, a score of one was assigned if "yes" was the response, whereas a score of zero was assigned otherwise (i.e., an answer of "no", "not applicable", "not reported", or "cannot determine"). A study-specific global score, ranging from zero to 14, was calculated by summing up scores across all criteria. A higher score indicates a better study quality. Study quality assessment helped measure strength of scientific evidence but was not used to determine the inclusion of studies.

Results

Study selection

Figure 1 shows the study selection flowchart. We identified a total of 14 183 articles through keyword and reference search, including 5 716 articles from PubMed, 8 242 articles from Web of Science, 224 articles from the Cochrane Library, and one article from Google Scholar through hand-searching. After removing duplicates, 13 013 articles underwent title and abstract screening, in which 12 996 articles were excluded. The remaining 17 articles were reviewed in full text against the study selection criteria. Of these, seven articles were excluded. The reasons for exclusion were that two articles were narrative review articles instead of original studies (Li et al. 2015; Lü et al. 2015), two articles were not based on

LMICs (Anowar et al. 2017; Di 2010), one article was a simulation study instead of a field study (de Sá et al. 2017), one article was a comment instead of an original study (Wang 2016), and one article did not report any outcome pertaining to health behaviors (Braniš and Větvička 2010). In total, ten articles were included in the review (An and Yu 2018; Chen and Lin 2016; Hu et al. 2017; Li and Kamargianni 2017, 2018; Yang and Zacharias 2016; Yu et al. 2017a; Yu et al. 2017b; Zhang and An 2018; Zhao et al. 2018).

Basic characteristics of the included studies

Table 1 summarizes basic characteristics of the 10 China-based studies included in the review, all published within the past three years (two in 2016, four in 2017, and four in 2018). Six of the 10 studies adopted a cross-sectional study design, and four adopted a longitudinal study design. The sample sizes ranged from 153 to 12 291: six studies had a sample size between 100 and 999, three between 1000 and 9 999, and one above 10 000. Four studies focused on adults aged 18 years and older, four studies focused on people of all ages, one study exclusively examined older adults, and one study did not report age. One study did not report the sex distribution in its sample, and the remaining nine studies recruited both sexes. The percentage of females across studies ranged from 30% to 62%, with a sample size-weighted average of 40%. A variety of statistical models were applied across studies, including logistic regression, multivariate nested logistic regression, multinomial logistic regression, multivariate analysis of variance, linear individual fixed-effect regression, and autoregressive moving-average model.

Table 2 summarizes the measures for air pollution and physical activity-related behaviors among the included studies. Eight studies used objective air pollution measures, and two used subjective air pollution measures reported by participants. Specific subjective measures of air pollution included questions such as "How severe is the air pollution in the area of your local residence?", or "How important is the role of air pollution in your decision with regard to bicycle commuting?" Objective air pollution measures were constructed based on data collected from the local environment monitoring sites in China. Specifically, four studies examined ambient $PM_{2.5}$ concentration, and the other six focused on overall air pollution and/or AQI. Three studies examined the relationship of $PM_{2.5}$ concentration and weekly physical activity. One study examined the relationship of daily air quality and television use, one study examined the relationship of daily $PM_{2.5}$ concentration and cycling choice, and one study examined the relationship of daily air pollution and transportation mode choice. Five studies adjusted for some individual characteristics (e.g., age, marital status, annual household income, body mass index, smoking status, drinking status, and self-rated physical health) in the statistical analyses, and four studies adjusted for certain weather conditions (e.g., temperature, precipitation, and wind velocity).

Physical activity-related behaviors included physical activity (n=4), physical inactivity (n=1), television use (n=1), and transportation mode (n=4). Eight studies measured health behaviors using questionnaires administered to participants themselves, whereas the remaining two studies used objective measures (The Nielsen Watchbox for measuring real-time television use and mobile app). Self-reported health behavior questionnaires included both standardized questionnaires (e.g., International Physical Activity Questionnaire [IPAQ]) and general questions (e.g., “How often do you engage in vigorous exercise for at least 20 minutes per day in a way that makes you sweat or breath heavier than usual?” or “How many days over the past seven days did you participate in sitting activities such as watching TV, using computer, reading, or doing handcrafts?”). Among the studies that used subjective health behavior measures, four used measures validated in previous research (i.e., IPAQ and Physical Activity Scale for the Elderly [PASE]).

Table 3 summarizes the key findings reported in the studies included in the review regarding the estimated impact of air pollution on health behaviors among Chinese residents. Chen and Lin (2016) examined the relationship between perceived air quality and physical inactivity among adults in China. They found that an improvement in perceived air quality was associated with a decline in physical inactivity rate (odds ratio = 0.80). Yang and Zacharias (2016) examined perceived air quality in relation to active commuting, and found that air pollution was a major deterrent for people’s decisions to commute by bicycle (odds ratio = 0.98). Hu et al. (2017) collected exercise data spanning 160 days from 153 mobile app users in China (Hu et al. 2017). This mobile app was used to record leisure-time physical activity as users needed to manually activate this app before starting exercises. Mobile app users were less likely to participate in outdoor running, biking, and walking activities as air pollution worsened, however, no difference in average distance and duration of exercise was found across different air pollution levels. It was concluded that people's participation in outdoor exercise was impeded by air pollution severity, but they tended to stick to their exercise routines if exercise was initiated. Li and Kamargianni (2017) examined air pollution in relation to transportation mode among residents in Taiyuan City. They found that severe air pollution was associated with reduced nonmotorized transportation such as biking and walking, whereas no association was found between air pollution and transportation mode when air pollution was moderate. Yu et al. (2017a) examined the longitudinal relationship between $PM_{2.5}$ and physical activity-related health behaviors among university retirees in Beijing, China. An increase in ambient $PM_{2.5}$ concentration by one standard deviation was associated with a reduction in weekly total hours of walking by 4.69, a reduction in leisure-time PASE score by 71.16, and a reduction in total PASE score by 110.67. Moreover, an increase in ambient $PM_{2.5}$ concentration by one standard deviation was associated with an increase in daily average hours of nighttime/daytime sleeping by 1.75. An and Yu (2018) and Yu et al. (2017b) assessed the impact of $PM_{2.5}$ air pollution on physical activity-related health behaviors among college students in Beijing, China. Health surveys were repeatedly administered among 12 000 newly admitted students at a major Chinese university during 2012–2015. Ambient $PM_{2.5}$ concentration was negatively associated with time spent on walking and vigorous physical activity, but positively associated with time spent on nighttime/daytime sleep among college freshmen. An increase in ambient $PM_{2.5}$ concentration by one standard deviation was associated with a reduction in weekly total minutes of walking by 7.3, a reduction in weekly total minutes of vigorous physical activity by 10.1, and an increase in daily average hours of nighttime/daytime sleep by 1.07. Zhang and An (2018) examined the impact of ambient air pollution on television use among residents in Shanghai, China. Device-measured daily average duration of television use during 2014–2016 was obtained from a random sample of 300 households linked to air pollution and weather data. The hypothesis was that ambient air pollution level as indicated by the AQI would be positively associated with daily television use through discouraging outdoor activities. In contrast to their hypothesis, fair and light air pollution, but not moderate-to-severe air pollution, was associated with reduced rather than increased television use. Compared to the days when air quality was good ($0 \leq AQI \leq 50$), days with fair air quality ($50 < AQI \leq 100$) and light air pollution ($100 < AQI \leq 150$) were associated with a reduction in daily average television use by 2.9 and 4.6 minutes, respectively; whereas moderate-to-severe air pollution ($AQI > 150$) was not found to be associated with daily average television use among Shanghai residents. In a cross-sectional study, Zhao et al. (2018) examined the impact of air pollution on cycling behavior when facing light, medium and heavy air pollution, and found that higher $PM_{2.5}$ concentration was associated with lower possibility of cycling among those who were male, over 30 years old, and of lower income.

Study quality assessment

Table 4 reports criterion-specific and global ratings from the study quality assessment for the included studies, which scored on average 9.5 out of 14, with a range from seven to 11. All studies included in the review clearly stated the research question and objective, specified and defined the study population, had a participation rate above 50%, recruited participants from the same or similar populations during the same time period, and pre-specified and uniformly applied inclusion and exclusion criteria to all potential participants. Seven studies implemented valid and reliable exposure measures, and examined different levels of the exposure in relation to the outcome. In contrast, none of the studies had the outcome assessors blinded to the exposure status of the participants, nor did they provide a sample size justification using power analysis. Two studies implemented valid and reliable outcome measures. Three studies measured exposures of interest prior to the outcomes.

Discussion

This study systematically reviewed scientific evidence linking ambient air pollution to physical activity-related behavior modifications in China. A total of 10 studies were identified. Six used a cross-sectional design and the remaining four used a prospective cohort design. Four studies assessed a specific air pollutant namely $PM_{2.5}$, whereas the remaining six focused on overall air quality using AQI. Decline in overall air quality and increase in $PM_{2.5}$ concentration were found to be associated with reduced daily/weekly duration of outdoor leisure-time and/or transportation-related physical activity such as walking, running and biking but increased duration of daytime/nighttime sleeping among Chinese residents. In contrast, evidence linking overall air quality and $PM_{2.5}$ concentration to sedentary behavior, such as watching TV, remains mixed and inconclusive.

Findings from this review coincide with the documented relationship between ambient air pollution and overall physical activity level in developed countries. Roberts et al. (2014) found that community-level air pollution was negatively associated with leisure-time physical activity among U.S. adults (Roberts et al. 2014). Wells et al. (2012) found that worsened air quality led to reduced time spent on outdoor activities in the U.S (Wells et al. 2012). Wen et al. (2009a) reported that media alerts of AQI contributed to decreased outdoor activities, especially in adults with asthma (Wen et al. 2009a). Findings from this review provided additional evidence linking air pollution to reduced overall physical activity level in China.

Evidence regarding the influence of overall air quality and $PM_{2.5}$ concentration on sedentary behavior remains lacking. Zhang and An (2018) reported that ambient air pollution was negatively associated with daily television use, but the association diminished as air quality further deteriorated. An and Yu (2018) and Yu et al (2017a) found that increased $PM_{2.5}$ concentration was associated with increased daily duration of sleeping among university freshmen and retirees in Beijing. Moreover, smog appearance of polluted air due to high particulate concentration may deter people from going outside but promote indoor activities, including sleep (Roberts et al. 2014). Therefore, it is possible that people spend more time sleeping instead of engaging in physical activity under severe ambient air pollution (An and Yu 2018; Yu et al. 2017a).

Despite some emerging evidence linking elevated air pollution level to reduced outdoor physical activity, several important limitations pertaining to the existing research remain to be addressed. Relevant studies are scarce and concentrated in a few countries such as the U.S. and China. Most studies adopted self-reported physical activity measures that are susceptible to recall error and social desirability bias. Most studies did not report whether participants were aware of air pollution or air pollution was communicated to participants. A majority of studies focused on $PM_{2.5}$ and/or overall air quality (e.g., AQI) but other major air pollutants (e.g., PM_{10}, CO, NO_x, O_3, and SO_x) are less studied. All studies are observational (i.e., cross-sectional or longitudinal) in design, so that the findings may not imply causality. Non-U.S. studies predominantly recruited convenience samples, which compromises the generalizability to populations at risk. It is also possible that study participants to some extent mediated the influence of air pollution by switching from outdoor to indoor physical activity, or delay activity until high air pollution days are over, but such coping mechanisms were largely unexamined in the literature. A discrepancy between self-perceived and objectively measured air pollution severity may be present and exert a differential impact on an individual's decision to exercise, but no study has examined such potential discrepancy. Most studies focused on healthy adults, whereas studies on susceptible subpopulations, such as children, older adults, and patients with chronic conditions (e.g., chronic obstructive respiratory disease, cardiovascular disease, stroke or asthma) remain limited, even though the AQHI provides targeted message for these susceptible groups (Government of Canada 2017). This review solely focused on peer-reviewed publications written in English. Articles written in Chinese or other non-English languages were excluded. To our knowledge, ambient air pollution in relation to physical activity-related behaviors is a new topic to research scholars in China. Relevant publications in Chinese can be scarce at the current stage but are expected to accumulate in the coming years.

Building upon previous research, future studies with the following features are warranted. Firstly, there is a need for studies with objective measures of physical activity (e.g., pedometer or accelerometer) that recruit large-scale nationally or regionally representative samples. Furthermore, future studies should consider examining susceptible populations such as children and patients with acute or chronic health conditions and follow them for an extended time period. New research should differentiate and contrast self-perceived versus objectively-measured air pollution levels in relation to behavioral modification and should attempt to assess people's decision making process regarding outdoor/indoor physical activity and sedentary behavior under different air pollution levels. In addition, researchers should also pay attention to whether and how air pollution is communicated to participants. Furthermore, it would be valuable to distinguish the impact of air pollution by physical activity type (e.g., walking, biking, or gardening) and intensity (e.g., light-, moderate-, or vigorous-intensity physical activity). Finally, future research should consider examining the influence of air pollution on physical activity in other countries and regions besides China.

Conclusion

This study systematically reviewed scientific evidence regarding the influence of ambient air pollution on physical activity-related behaviors in China. Ten studies met the selection criteria and were included in the review. Decline in overall air quality and increase in $PM_{2.5}$ concentration were found to be associated with reduced daily/weekly duration of outdoor leisure-time and/or transportation-related physical activity such as walking, running and biking but increased duration of daytime/nighttime sleeping among Chinese residents. In contrast, evidence linking overall air quality and $PM_{2.5}$ concentration to sedentary behavior remains mixed and inconclusive. Future studies adopting objective measures of physical activity and longitudinal/experimental design are warranted to examine the impact of air pollution on susceptible populations such as children and fragile older adults and residents in other developing countries besides China.

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Figure 1 Study selection flowchart

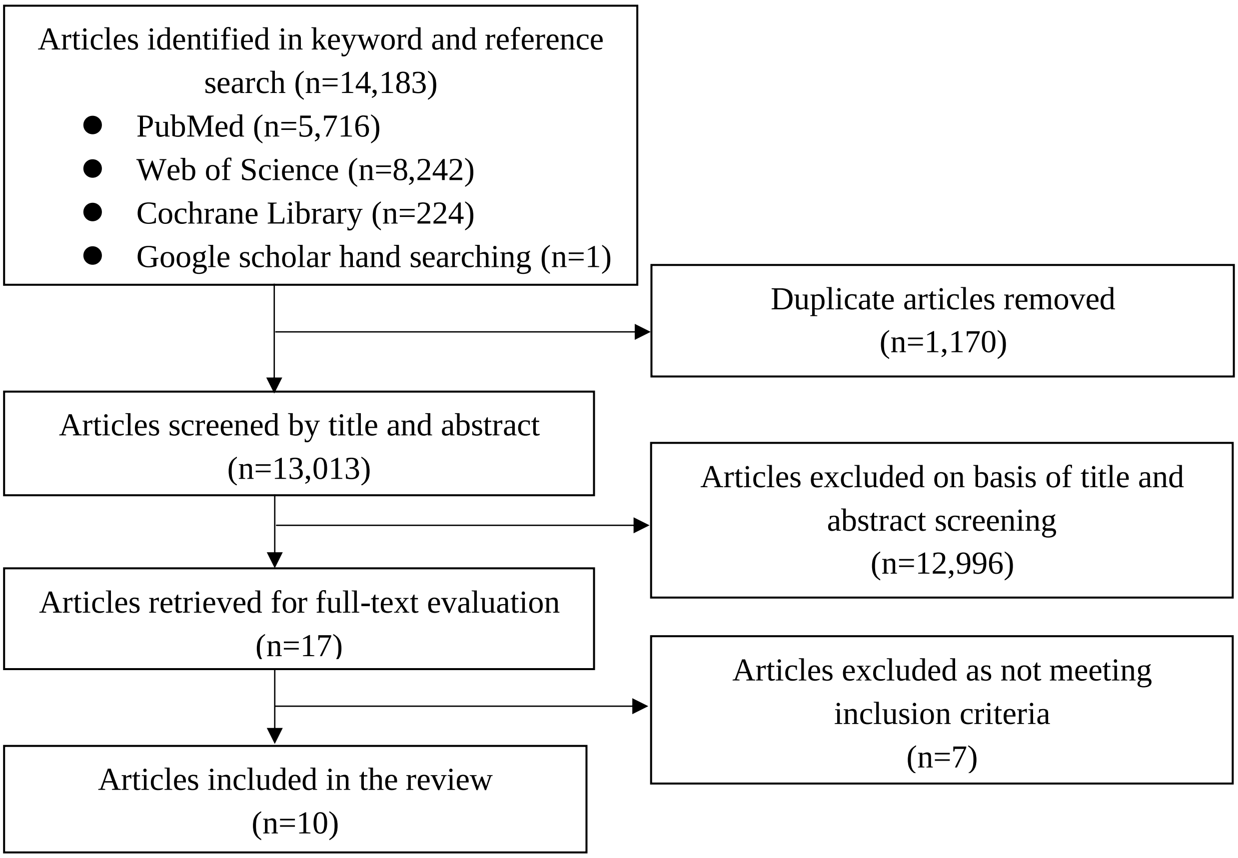

Table 1 Basic characteristics of the studies included in the review

Study ID	Authors, year	Country/city	Study design	Sample size	Age (years)	Female (%)	Sample characteristics	Statistical model	Study period	Setting
1	Chen & Lin, 2016	China	Cross-sectional	2268	42–49	52	Residents	Multivariate nested logistic regression	2010–2011	Urban
2	Yang & Zacharias, 2016	Beijing, China	Cross-sectional	852	≥60	41	Residents	Binary logistic regression	2013	Urban
3	Hu et al., 2017	China	Cross-sectional	153	36.8±7.9	30	App users	Multivariate analysis of variance	2014–2015	
4	Li & Kamargianni, 2017	Taiyuan, China	Cross-sectional	492	All ages	52	Residents	Multinomial logistic model	2015–2016	
5	Yu et al., 2017a	Beijing, China	Longitudinal	848–890	66.8 (95% CI: 66.4–67.3)	62 (95% CI: 59–65)	University retirees	Linear fixed-effect regression	2011–2016	Urban
6	Yu et al., 2017	Beijing, China	Longitudinal	3223–3242	18.2±0.9	32	University freshmen	Linear fixed-effect regression	2012–2013	Urban
7	An & Yu, 2018	Beijing, China	Longitudinal	12,184–12,291	18.1 (95% CI: 18.0–18.1)	33 (95% CI: 32–34)	University freshmen	Linear fixed-effect regression	2012–2015	Urban
8	Li & Kamargianni, 2018	Taiyuan, China	Cross-sectional	4769	All ages	49	Residents	Multivariate nested logistic regression	2015	Urban
9	Zhang & An, 2018	Shanghai, China	Longitudinal	300			Residents	Autoregressive moving-average model	2014–2016	
10	Zhao et al., 2018	Beijing, China	Cross-sectional	307	All ages	50	Residents	Binary logistic and multinomial logistic model	2015	Urban and suburb

Table 2 Measures of air pollution and health behavior in the studies included in the review

Study ID	Type of air pollution measure	Detailed measure of air pollution	Type of health behavior measure	Detailed measure of health behavior	Adjusted covariates
1	Self-report questionnaire	Perceived air quality	Self-report questionnaire	Physical inactivity	Gender, age, marital status, chronic disease status, overweight status, psychological distress, country
2	Self-report questionnaire	Air pollution	Self-report questionnaire	Commute by bicycle	
3	Ministry of Environmental Protection, China	Air quality	Objective measure	Outdoor exercises	Age, sex
4	Ministry of Environment Protection, China, and Shanxi Meteorology	Daily air pollution	Self-report questionnaire	Mode choice behavior	
5	Mission China air quality monitoring program	Average ambient $PM_{2.5}$ concentration	Self-report questionnaire	Weekly hours of sedentary behavior, walking, biking, and motorized transportation; Leisure-time Physical Activity Scale for the Elderly (PASE) score; total PASE score; daily hours of sleeping	Age, marital status, annual household income, body mass index, smoking status, self-rated health, number of chronic diseases, days in hospital or homecare in last year, average daytime temperature, average wind speed, and percentage of rainy days over the last 7 days
6	Mission China air quality monitoring program	Hourly ambient $PM_{2.5}$ concentration	Self-report questionnaire: The short version of the International Physical Activity Questionnaire	Physical activity	Age, body mass index, current smoking status, current drinking status, self-rated physical health, self-rated mental health, average daytime temperature, average wind speed and percentage of rainy days in the last 7 days
7	Mission China air quality monitoring program	Average ambient $PM_{2.5}$ concentration	Self-report questionnaire: International Physical Activity Questionnaire	Total minutes of vigorous physical activity and walking in the last week; daily hours of sedentary behavior in the last week	Age, body mass index, current smoking status, current drinking status, self-rated physical health, self-rated mental health, average daytime temperature, average wind speed and percentage of rainy days in the last 7 days
8	Self-report questionnaire	Air pollution	Self-report questionnaire	Transport mode	
9	Shanghai Environmental Monitoring Center	Daily air quality index (AQI)	Objective measure	Daily average duration of television use	Daily maximum air temperature, a rainy day, wind velocity, day of the week, month of the year, year, national holiday
10	Beijing Municipal Environmental Protection Bureau	Daily average $PM_{2.5}$ concentration	Self-report questionnaire	Cycling experiences and daily cycling trip information	

Table 3 Estimated effects of air pollution on health behavior in the studies included in the review

Study ID	Estimated effects of air pollution on health behavior	Main findings
1	One-unit increase of perceived air quality is associated with a reduction in physical inactivity by 20% (OR=0.80, 95% CI = 71%, 89%).	Improved perceived air quality was associated with decreased likelihood of physical inactivity.
2	Air pollution, traffic safety, the lack of road space, climatic disadvantages, insufficient secure parking for bicycles, and inadequate night lighting are seen as major barriers by all commuters.	Air pollution might be a major and increasing obstacle for bicycle use in Beijing.
3	App users were less likely to participate in outdoor running, biking, and walking ($F = 24.16$, $p < 0.01$) when air pollution concentration increased.	People's participation in outdoor exercise was impeded by air pollution severity, but they stick to their exercise routines once exercise was initiated.
4	In winter, biking (Coefficient = -0.009, t-Statistic = -2.63), bike-sharing (Coefficient = -0.058, t-Statistic = -6.71), and walking (Coefficient = -0.018, t-Statistic = -5.12) were not preferred when air pollution level increased. Instead travelers switched to the use of cars (Coefficient = 0.015, t-Statistic = 5.63), buses (Coefficient = 0.0002, t-Statistic = 0.06), taxis (Coefficient = 0.003, t-Statistic = 0.65), and electric bikes (Coefficient = 0.003, t-Statistic = 1.35). In summer, air pollution was negatively correlated with walking (Coefficient = -0.001, t-Statistic = -0.13) but positively correlated with biking (Coefficient = 0.016, t-Statistic = 1.85) and bike-sharing (Coefficient = 0.017, t-Statistic = 2.20).	Improved air quality had a positive impact on nonmotorized transport use. Severe air pollution could discourage the use of all nonmotorized transport modes (e.g., biking, bike-sharing, walking). However, when air pollution became moderate, a change in air pollution level did not have a significant impact on mode choice.
5	An increase in ambient $PM_{2.5}$ concentration by 1 standard deviation (56.6 $\mu g/m^3$) was associated with a reduction in weekly total hours of walking by 4.69 (95% CI = 1.30, 8.08), a reduction in leisure-time Physical Activity Scale for the Elderly (PASE) score by 71.16 (95% CI = 28.91, 113.41), and a reduction in total PASE score by 110.67 (95% CI = 59.25, 162.08). An increase in ambient $PM_{2.5}$ concentration by one standard deviation was associated with an increase in daily average hours of nighttime/daytime sleeping by 1.75 (95% CI = 1.24, 2.26).	Air pollution significantly discouraged Chinese older adults from engaging in daily physical activities.
6	An increase in ambient $PM_{2.5}$ concentration by one standard deviation (44.72 $\mu g/m^3$) was associated with a reduction in 22.32 weekly minutes of vigorous physical activity (95% CI = 19.77, 24.88), a reduction in 10.63 weekly minutes of moderate physical activity (95% CI = 6.64, 14.61), a reduction in 32.45 (95% CI: 27.28, 37.63) weekly minutes of moderate to vigorous physical activity (MVPA),	Ambient $PM_{2.5}$ air pollution significantly discouraged physical activity among Chinese freshmen students living in Beijing.

	and a reduction in 226.14 (95% CI = 256.06, 196.21) weekly physical activity MET-minute scores.	
7	An increase in the ambient $PM_{2.5}$ concentration by one standard deviation (36.5 μg/m^3) was associated with a reduction in weekly total minutes of walking by 7.3 (95% CI = 5.3, 9.4), a reduction in weekly total minutes of vigorous physical activity by 10.1 (95% CI = 8.5, 11.7), a reduction in daily average hours of sedentary behavior by 0.06 (95% CI = 0.02, 0.10).	Ambient $PM_{2.5}$ air pollution was inversely associated with physical activity level.
8	Air pollution had significant negative effect on bike-sharing choice (Coefficient = -0.0045, t-Statistic = -8.29); Air pollution also had significant negative impact on walking (Coefficient = -0.0045, t-Statistic = -9.17), electric bike use (Coefficient = -0.0022, t-Statistic = -3.93), and bus use (Coefficient = -0.0020, t-Statistic = -2.65); Car-sharing (Coefficient = 0.0023, t-Statistic = 1.96) was the only transportation mode that had a positive correlation with air pollution level.	Air pollution had significant negative effect on bike-sharing choice. Apart from bike-sharing, air pollution also has significant negative impact on walking, electric bike and bus choices. Car-sharing is the only mode that displays positive correlation between its utility and higher air pollution level. Bus usage is negatively correlated with air pollution. However, younger and less wealthy people would still use bus service even if air quality became worse.
9	There was a negative non-linear relationship between air pollution level and television use. Compared to the days when air quality was good ($0 \leq AQI \leq 50$), days with fair air quality ($50 < AQI \leq 100$), light air pollution ($100 < AQI \leq 150$), and moderate-to-severe air pollution ($AQI > 150$) were associated with a reduction in daily average television use by 2.9 ($p = 0.002$), 4.6 ($p < 0.001$), and 1.9 ($p = 0.369$) minutes, respectively.	Modest but not more severe air pollution was associated with reduced television use.
10	Residents with lower income (Coefficient = 0.58, 95% CI = -0.00, 1.16), those over 30 years old (Coefficient = 0.67, 95% CI = 0.11, 1.22), and male respondents were more likely to continue cycling in hazy weather.	Hazy weather could reduce cycling and encourage people to switch to other travel modes, especially motorized travel modes. Higher $PM_{2.5}$ concentration contributes to a lower possibility of continuing cycling, with socio-economic variations. People with higher probabilities of persisting in cycling in polluted air are more likely to be male, over 30 years, lower income, and those who live outside the city center.

Table 4 Study quality assessment

Criterion \ Study ID	1	2	3	4	5	6	7	8	9	10
1. Was the research question or objective in this paper clearly stated?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
2. Was the study population clearly specified and defined?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3. Was the participation rate of eligible persons at least 50%?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study pre-specified and applied uniformly to all participants?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5. Was a sample size justification, power description, or variance and effect estimates provided?	N	N	N	N	N	N	N	N	N	N
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	N	N	N	N	Y	Y	Y	N	N	N
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	Y	N	Y	Y	Y	Y	Y	N	Y	N
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	N	N	Y	Y	Y	Y	Y	N	Y	Y
10. Was the exposure(s) assessed more than once over time?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	N	N	Y	N	N	N	N	N	Y	N
12. Were the outcome assessors blinded to the exposure status of participants?	N	N	N	N	N	N	N	N	N	N
13. Was loss to follow-up after baseline 20% or less?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	Y	N	Y	N	Y	Y	Y	N	Y	N
Total score	9	7	11	9	11	11	11	7	11	8

Notes: This study quality assessment tool was adopted from the National Institutes of Health's Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies. For each criterion, a score of one was assigned if "Y" was the response, whereas a score of zero was assigned otherwise. A study-specific global score, ranging from zero to 14, was calculated by summing up scores across all 14 criteria. Study quality assessment helped measure strength of scientific evidence, but was not used to determine the inclusion of studies.