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Research paper

Cross-sectional associations between long-term exposure to particulate matter and depression in China: The mediating effects of sunlight, physical activity, and neighborly reciprocity

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ABSTRACT

Background: Although numerous studies have speculated about the direct and indirect linkage between long-term air pollution (i.e., $PM_{2.5}$) concentrations and mental health in developed countries, evidence for developing countries is limited. Our aim was to examine the mediation effects of sunlight, physical activity, and neighborly reciprocity on the association between air pollution and depression.
Methods: In a sample of 20,861 individuals in China in 2016, depression was measured using the Center for Epidemiological Studies Depression screener (CES-D) and linked to annual city-wide $PM_{2.5}$ data. We used multilevel regression models to assess the associations between depressive symptoms and $PM_{2.5}$ and tested the mediation of sunlight, physical activity, and neighborly reciprocity in this association. Propensity score matching was used to evaluate whether selection bias may affect the association between CES-D scores and $PM_{2.5}$.
Results: $PM_{2.5}$ concentration was positively associated with depression symptoms. All mediators were significantly and negatively associated with $PM_{2.5}$. Our mediation analyses indicated that physical activity, neighborly reciprocity, and exposure to sunlight are important mechanisms through which $PM_{2.5}$ affects depressive symptoms.
Limitations: The limitations of the present study were the cross-sectional nature of the data and modifiable areal unit problem.
Conclusions: Our findings suggest not only that $PM_{2.5}$ is directly associated with depression, but also that this association seems to be partially mediated by physical activity, neighborly reciprocity, and sunlight.

1. Introduction

Depression is a serious public health issue in developing countries (Adjayegbewonyo et al., 2018; Wang et al., 2018a; Wang et al., 2018b) and one of the top three diseases that lead to disability (Murray et al., 2012; Vos et al., 2016). It is a pressing concern in China, where 25% of the population suffer from depressive disorders (China Labor-force Dynamics Survey, 2016). A plethora of studies have shown that depression not only causes a reduction in quality of life but also increases the risk of chronic physical illnesses (Kooy et al., 2007; Farrokhi et al., 2014; Hare et al.; 2014; Moussavi et al., 2007; Pinquart and Duberstein, 2010; Psaltopoulou et al., 2013; Rumsfeld et al., 2005; Ruo et al., 2003; Stewart et al., 2003).

Until recently, most scholarly efforts have explored factors that contribute to the development of mental disorders such as personality traits, genetics, and drug use (Adjayegbewonyo et al., 2018; Ni et al., 2017; Wang et al., 2018a). Scientific evidence is mounting that residential environments also contribute to the risk of mental health problems (Groenewegen et al., 2018; Helbich, 2018). Among various environmental risk factors, air pollution has received considerable attention (Brunekreef and Holgate 2002; Hwa-Lung et al., 2010; Kim et al., 2010; Wang et al., 2014; Wen et al., 2009; Wong et al., 2009; Zhang et al., 2018). A recent literature review suggested that long-term exposure to air pollution exerts a detrimental effect on mental health

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and increases the risk of mental disorders (Buoli et al., 2018). However, empirical studies dealing with the associations between air pollution exposure and mental health have yielded inconsistent results (Kioumourtzoglou et al., 2017; Lim et al., 2012).

Many studies have investigated the biological processes linking air pollution to depression (Cho et al., 2014; Chuang et al., 2007; Nel, 2005; Pope et al., 2004; Pun et al., 2017; Seaton et al., 1995). One potential biological pathway is that fine particulate matter with a diameter of 2.5 μm or less ($PM_{2.5}$) may cause environmentally induced inflammation and oxidative stress, which are implicated in the pathogenesis of depression (Cho et al., 2014; Chuang et al., 2007; Nel, 2005; Pope et al., 2004; Pun et al., 2017; Seaton et al., 1995). For example, solid particles in the air can enter the blood stream and damage the cardiovascular system, and this inflammation may increase the risk of depression (Cho et al., 2014; Kioumourtzoglou et al., 2017; Lim et al., 2012; Naarding et al., 2005; Ng et al., 2008; Szyszkowicz, 2007; Szyszkowicz et al., 2009; Wang et al., 2014). Harmful particles may also enter the brain via the circulatory system and cause neuroinflammation, oxidative stress, cerebrovascular damage, and neurodegenerative pathology, which may dampen individuals' mood and increase the risk of depression (Kioumourtzoglou et al., 2017; Lim et al., 2012; Naarding et al., 2005; Ng et al., 2008; Szyszkowicz, 2007; Szyszkowicz et al., 2009; Wang et al., 2014). Recent studies showed that individuals who inhaled harmful particles had a higher risk of inflammation of the respiratory mucosa, therefore facing a higher risk of depression (Buoli et al., 2018; Cho et al., 2014).

A second pathway linking air pollution and depression is through physical activity. Pronounced air pollution may decrease the willingness to perform outdoor physical activities, which are well-known to be beneficial for individuals' health (An et al., 2015; Benedetti et al., 2001; Kent et al., 2009; Kioumourtzoglou et al., 2017; Robert et al., 2014; Sinharay et al., 2018). For example, Giles and Koehle (2014) found that exposure to air pollution not only exerted a negative effect on pulmonary, cardiovascular, cognitive, and systemic functions, but also affected maximal oxygen consumption and exercise performance. Others reported that air pollution mitigated the health benefits of physical activities (Andersen et al., 2015; McCreanor et al., 2007; Mills et al., 2007; Sinharay et al., 2018).

A third pathway is that air pollution may discourage individuals to socialize with neighbors in public spaces, which reduces their chances of seeking social support from their neighbors as well as providing it. As neighborly reciprocity is a protective factor against depression, exposure to air pollution may thus increase the risk of depression (Fan et al., 2011; Kim et al., 2010; Maas et al., 2009; Pimpin et al., 2018; Wong et al., 2009). In addition, higher levels of $PM_{2.5}$ concentration are usually accompanied by increased smog, which reduces the protective effect of sunlight (Benedetti et al., 2001; Kent et al., 2009). Sunlight may trigger the release of serotonin, which makes individuals feel released and focused. Individuals who lack of sufficient light exposure may have a low level of serotonin, and are thus more likely to feel anxious and depressed (Benedetti et al., 2001; Kent et al., 2009).

Although a negative association between air pollution and mental health status has been observed in the Chinese context (Chan and Yao, 2008; Chen et al., 2018; Li et al., 2014; Lin et al., 2016; Wang et al., 2018b; Xu, Gao et al., 1994; Yin et al., 2018; Zhang et al., 2011; Zhang et al., 2017), insufficient attention has been paid to the effect of air pollution on depression as a specific type of mental disorder. Only a few studies have estimated the direct effect of air pollution on depression in China (Chen et al., 2018; Tian et al., 2015; Wang et al., 2018b), but they failed to systematically explore biopsychosocial pathways such as physical activity and neighborhood social cohesion.

To fill this research gap, this study represents the first attempt to systematically explore biopsychosocial pathways linking air pollution to depression in China. Empirically, we examined the association among $PM_{2.5,}$ depression, physical activities, neighborly reciprocity, and exposure to sunlight using multilevel regression and mediation analysis. Fig. 1 illustrates our conceptual model. The level of $PM_{2.5}$ was hypothesized to be positively related depression. We further hypothesized that the concentration of $PM_{2.5}$ would influence the risk of depression through three pathways: reduction in time spent on outdoor physical activities, decline in reciprocity among neighbors, and decrease in exposure to natural sunlight.

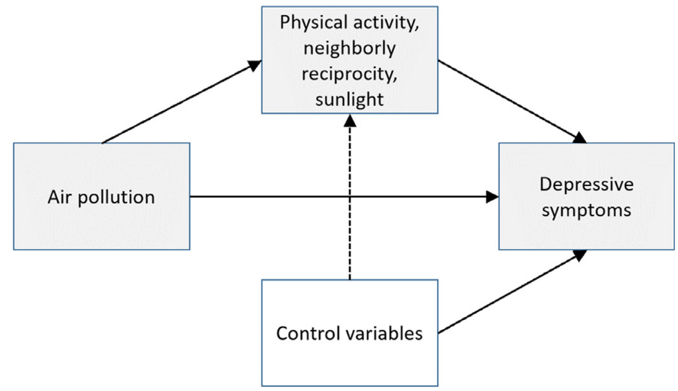

Fig. 1. Conceptual model how the moderators affect the $PM_{2.5}$ and depression relation.

2. Materials and methods

2.1. Study population

Data were derived from the 2016 wave of the China Labor-force Dynamics Survey (CLDS). The CLDS was primarily conducted by the Center for Social Survey at Sun Yat-Sen University. The survey data were collected using a multi-stage, cluster, stratified probability-proportional-to-size sampling approach. In the first stage, 158 prefecture-level administrative divisions were randomly selected from 29 provinces. In the second stage, 401 neighborhoods were randomly sampled from the chosen administrative divisions. Finally, 21,086 individuals were randomly selected from the sampled neighborhoods. We excluded 225 respondents missing essential information, resulting in a final sample size of 20,861. The Ethics Committee of the Department of Sociology and Social Work at Sun Yat-Sen University approved the study design. The authors received permission from the Center for Social Survey at Sun Yat-Sen University to use the CLDS data. Written consent was obtained from each CLDS respondent at the time of the survey.

2.2. Data

2.2.1. Depression

Depressive symptoms were assessed using the Center for Epidemiology Studies-Depression scale (CES-D) (Radloff, 1977), a composite measure of 20 items assessing depressive symptoms during the previous week. Individual items are designed to assess respondents' depression-related feelings, including happiness, hopelessness, etc. Each item is rated on a 4-point scale ranging from 0 ("rarely or none of the time") to 3 ("most or almost all of the time"). To consider the entire spectrum from none to severe depressive symptoms and circumvent problems of setting subjective cut-off points, we used the total score (i.e., the higher the score, the more depressive symptoms). The CES-D has been proven to have good validity and reliability in the general population (Zich et al., 1990) and is widely used in environmental epidemiological studies (Wang et al., 2018a). Cronbach's alpha demonstrated a good internal consistency of the scale (0.95). The CES-D score took the form of a continuous variable.

2.2.2. Air pollution

Data on $PM_{2.5}$ concentration were derived from the Airborne Fine Particulate Matter and Air Quality Index website (AFPMAQI, 2016). $PM_{2.5}$ data for 2016 were extracted from a nationwide measurement network comprising 1613 monitoring stations distributed across China. To represent long-term exposures, we calculated the average annual $PM_{2.5}$ concentration in each city by aggregating hourly air pollution data from each station (Kioumourtzoglou et al., 2017; Lim et al., 2012; Wang et al., 2018b; Wang et al., 2014; Yin et al., 2018). On average, the level of $PM_{2.5}$ was 70.35 μg/m^3 (Standard Deviation: 37.79 μg/m^3). In account of a skewed distribution, we log-transformed this variable.

2.2.3. Mediators

We examined whether physical activities, neighborly reciprocity, and exposure to natural sunlight mediated the relationship between the level of $PM_{2.5}$ and depression. Operationally, we used time spent on physical activities per week to measure the intensity of physical activities. We used a binary variable to measure the respondents' perception of neighborly reciprocity (Fan et al., 2011; Kawachi et al., 1999; Maas et al., 2009). The variable was coded as 1 if a respondent reported that his/her neighbors always or often helped each other, and as 0 otherwise. We used a binary variable to measure the respondents' perception of sunlight exposure within a neighborhood (1 = there was a sunny day, 0 = otherwise).

2.2.4. Control variables

We adjusted for 12 potentially confounding covariates following the literature (Kioumourtzoglou et al., 2017; Lim et al., 2012; Wang et al., 2018b; Yang et al., 2018): gender, age, marital status, educational attainment, employment status, hukou status, urbanicity, smoking status, drinking status, participation in medical insurance, presence of physical illness, and annual household income per household member. Table 1 shows summary statistics for all variables.

2.3. Statistical analyses

Multilevel regressions were performed to estimate the associations between depressive symptoms and the level of $PM_{2.5}$ (Goldstein, 2011). Such a modeling framework explicitly accounts for the hierarchical nature of the data (i.e., individuals nested in cities). Mediation analysis was conducted following the multistep procedure suggested by Baron and Kenny (1986). The objective of mediation analysis is to investigate whether predictors affect an outcome directly or indirectly through mediating variables. We used a stepwise approach to test the existence of three biopsychosocial pathways: first, we regressed the three mediators on the level of $PM_{2.5}$ and covariates (Models 1a–c); second, we regressed the CES-D score on the level of $PM_{2.5}$ and covariates (Model 2); third, we regressed the CES-D score on the level of $PM_{2.5}$, the three mediators, and the covariates (Model 3); fourth, we used the Sobel test (Sobel, 1982) and multiple mediation test (Preacher and Hayes, 2008) to test the significance of the mediation effects. In addition, to test whether the associations between the three mediators and CES-D scores varied with the level of $PM_{2.5}$, we added interaction terms between the level of $PM_{2.5}$ and the three mediators to Model 3 (Model 4).

Finally, we used propensity score matching techniques to partially address selection bias due to observed individual characteristics (Rosenbaum and Rubin, 1983) (Models 5a–d). We assumed that the positive relationship between the level of $PM_{2.5}$ and depression would remain when self-selection was accounted for. Individuals were matched based on propensity scores using several matching strategies including *k*-nearest neighbor matching, radius matching, kernel matching, and local linear regression matching (Dehejia and Wahba, 2002; Rubin and Thomas, 2000). The average treatment effect on the treated (ATT) was estimated to represent the effect of $PM_{2.5}$ concentration on depression, which was computed as the difference between the treatment group (i.e., individuals who were more exposed to concentrated $PM_{2.5}$) and the control group (i.e., individuals who were less exposed to concentrated $PM_{2.5}$). To ensure the robustness of our test, we defined individuals who ranked in the top 25%, 50%, and 75% in terms of the level of $PM_{2.5}$ in their cities as the treatment group and others as the control group. We defined $p < .05$ as statistically significant.

Table 1
Statistical summary of the variables.

Variables	Proportion (%)	Mean (SD)	Min.	Max.
Outcome				
CES-D score		7.39 (9.24)	0.00	60.00
Predictors				
The level of $PM_{2.5}$ (in log, μg/m^3)		70.35 (37.79)	12.80	184.50
Mediators				
Time spent on physical exercises (in log, minutes/week)		97.51 (267.95)	0.00	3361.00
The level of reciprocity among neighbors				
Low	52			
High	48			
Self-perceived sunlight (%)				
It is a sunny day in my neighborhood	54			
It is a cloudy/overcast day in my neighborhood	46			
Covariates				
Gender (%)				
Female	52			
Male	48			
Age (years)		44.83 (14.61)	18.00	76.00
Marital status (%)				
Married and living with spouse	73			
Married but not living with spouse	8			
Single, divorced, or widowed	19			
Education (%)				
College or above	13			
Secondary school	52			
Primary school or below	35			
Employment (%)				
Unemployed	5			
Employed	95			
Hukou status (%)				
Non-local hukou	9			
Local hukou	91			
Urbanicity (%)				
Rural area	61			
Urban area	39			
Current smoker (%)				
Yes	27			
No	73			
Current drinker (%)				
Yes	19			
No	81			
Participation in medical insurance (%)				
No	10			
Yes	90			
The presence of physical illness (%)				
No	89			
Yes	11			
Annual household income per household member (Chinese yuan/person, in 1000)		17.99 (202,48)	0.75	1500.00

Table 2
The association between the level of $PM_{2.5}$, time spent on physical exercises, the level of reciprocity among neighbors and exposure to sunlight.

	Model 1a: Time spent on physical exercises Coef. (SE)	Model 1b: The level of reciprocity among neighbors OR (CI)	Model 1c: Sunlight OR (CI)
Predictor			
The level of $PM_{2.5}$	−0.144**(0.072)	0.943**(0.761–0.968)	0.094***(0.049–0.181)
Covariates			
Male (ref: female)	0.069*(0.042)	0.955(0.883–1.033)	1.016(0.926–1.115)
Age	0.014***(0.001)	1.013***(1.010–1.016)	0.999(0.996–1.002)
Marital status (ref.: single, divorced, or widowed)			
Married and living with spouse	−0.578***(0.049)	1.213***(1.107–1.329)	0.979(0.881–1.089)
Married but not living with spouse	−0.744***(0.072)	1.214***(1.062–1.388)	1.080(0.923–1.263)
Education (ref.: primary school or below)			
College or above	0.970***(0.067)	1.092**(1.012–1.178)	0.874(0.756–1.011)
Secondary school	0.514***(0.041)	0.915(0.807–1.038)	1.020(0.932–1.116)
Employed (ref: unemployed)	−0.103(0.073)	1.149**(1.003–1.315)	0.982(0.840–1.149)
Urban area (ref: rural area)	0.811***(0.051)	0.519***(0.472–0.570)	0.992(0.883–1.114)
Local *hukou* (ref: non-local *hukou*)	0.345***(0.066)	1.784***(1.564–2.035)	0.913(0.797–1.047)
Current smoker (ref: current non-smoker)	−0.290***(0.047)	1.120**(1.025–1.222)	0.961(0.866–1.065)
Current drinker (ref: current non-drinker)	0.122***(0.047)	1.082*(0.992–1.180)	0.909*(0.822–1.006)
Participate in medical insurance (ref: not participate)	0.265***(0.055)	1.339***(1.206–1.487)	1.105*(0.983–1.241)
Presence of physical illness (ref: no presence)	−0.086(0.054)	0.902**(0.817–0.996)	0.952(0.850–1.066)
Annual household income per household member	0.120***(0.017)	1.028*(0.995–1.061)	1.032*(0.994–1.072)
Constant	−1.295***(0.437)	0.212***(0.083–0.544)	4.836***(3.482–6.718)
Variance (Constant)	0.481***	0.628***	7.430***
Variance (Residual)	5.382***		
Number of individuals	20,861	20,861	20,861
Number of neighborhoods	158	158	158
AIC	94,718	525,647	19,351

Note: Model 1a was estimated by means of a Gaussian link function, while for Models 1b and 1c a logit function was used. Odd ratios (OR) and 95% confidence interval (CI) were adopted for Models 1b and 1c. SE refers to the standard error. Significance levels:
$*p < .10$, $**p < .05$, $***p < .01$.

3. Results

We tested the relationships between $PM_{2.5}$ and the mediators using fully adjusted models (Table 2). In Model 1a, residents of polluted areas had significantly lower physical activity levels. In Model 1b, the level of reciprocity among neighbors was negatively associated with $PM_{2.5}$ concentration. Model 1c showed that the odds of residents being exposed to a sunny day in the neighborhood was also negatively associated with $PM_{2.5}$ levels.

Table 3 shows the extent to which the level of $PM_{2.5}$ is related to residents' CES-D scores when mediators are not included (Model 2) and included (Model 3). We found a highly significant and positive association between the level of $PM_{2.5}$ and CES-D scores. Model 3 showed a negative association between each of the three mediators (intensity of physical activities, perception of neighborly reciprocity, and perception of natural sunlight exposure) and CES-D scores. Model 3 demonstrated that the relationship between the level of $PM_{2.5}$ and CES-D scores remained significant after adjustment for the three mediators. Results of the Sobel test and multiple mediation tests suggested that the association between the level of $PM_{2.5}$ and depression was partially mediated by all three mediators. Results of the cross-level interaction from Model 4 indicated that the level of $PM_{2.5}$ significantly moderated the relationship between any of the three mediators and CES-D scores. $PM_{2.5}$ concentration weakened the negative association of physical activity, level of reciprocity among neighbors, and sunlight with CES-D scores. However, Akaike information criterion (AIC) suggested that adding interaction terms to Model 3 did not improve the model fit.

Finally, propensity score-matching was employed to address selection bias in Model 2. Table 4 (Models 5a–c) shows that urban dwellers with higher $PM_{2.5}$ levels had higher CES-D scores compared to residents of less polluted areas. Minor changes were observed across the application of different score-matching methods. The value of ATT was lower and less significant when the treatment condition was defined as residents of cities whose $PM_{2.5}$ concentrations ranked among the top 75%. This indicated that the linkage between $PM_{2.5}$ concentration and depression was stronger in more polluted areas.

4. Discussion

Previous studies have investigated the direct association between air pollution and depression in China without exploring underlying biopsychosocial pathways. This study moves a step further by examining the extent to which physical activities, neighborly reciprocity, and exposure to natural sunlight mediate the relationships between the level of $PM_{2.5}$ and depression. One of the strengths of this study is the use of nationally representative survey data collected across the entire country rather than small-scale survey data from a specific region or city.

One of our key findings was that the level of $PM_{2.5}$ was significantly related to depression. A possible explanation for this observation is that $PM_{2.5}$ may lead to the inflammation of different bodily organs, which increases the risk of depression-related physical diseases. For instance, studies in China found that solid particles in the air can increase blood pressure and cause cardiovascular diseases including hypertension and stroke (Dong et al., 2013a; b). $PM_{2.5}$ also affects individuals' nervous system by means of cerebrovascular and neural inflammation (Yin et al., 2018; Zhang et al., 2018). As the level of $PM_{2.5}$ is relatively high in China, residents inhaling harmful particles may also develop inflammation of the respiratory mucosa, which increases the risk of respiratory disease (Chen et al., 2016; Dong et al., 2012).

Although our study did not explore the above-mentioned inflammatory pathways, it enhances our knowledge of air pollution-depression relationships by investigating three biopsychosocial pathways: physical activities, neighborly reciprocity, and exposure to sunlight. Our results showed that $PM_{2.5}$ concentration was negatively related to respondents' time spent on outdoor physical activities. This finding confirms earlier ones that air pollution may decrease not only residents' willingness to go out to exercise but also the health effects of performing outdoor physical activities (Li et al., 2014; Yu et al., 2017a; Yu et al., 2017b). Additionally, the level of $PM_{2.5}$ was found to be

Table 3
The linkage between the level of $PM_{2.5}$ and CES-D score: The mediating effect of physical exercises, reciprocity among neighbors, and exposure to sunlight.

	Model 2 Coef. (SE)	Model 3 Coef. (SE)	Model 4 Coef. (SE)
Predictor			
The level of $PM_{2.5}$	2.540***(0.338)	1.107***(0.331)	1.346***(0.367)
Mediators			
Time spent on physical exercises		−0.120***(0.025)	−0.119***(0.025)
The level of reciprocity among neighbors		−1.270***(0.130)	−1.275***(0.130)
Sunny day (ref.: cloudy)		−0.248**(0.121)	−0.239**(0.121)
Covariates			
Male (ref: female)	−1.298***(0.156)	−1.299***(0.155)	−1.302***(0.156)
Age	0.025***(0.005)	0.030***(0.005)	0.031***(0.005)
Marital status (ref.: single, divorced, or widowed)			
Married and living with spouse	−0.752***(0.268)	−1.063***(0.267)	−1.063***(0.181)
Married but not living with spouse	−1.042***(0.181)	−0.789***(0.153)	−0.789***(0.267)
Education (ref.: primary school or below)			
College or above	−1.417***(0.249)	−1.332***(0.249)	−1.344***(0.249)
Secondary school	−1.276***(0.154)	−1.193***(0.154)	−1.195***(0.154)
Employed (ref: unemployed)	−0.531***(0.271)	−0.506*(0.270)	−0.512*(0.270)
Urban area (ref: rural area)	−0.175(0.188)	−0.262(0.188)	−0.266(0.189)
Local *hukou* (ref: non-local *hukou*)	−0.466*(0.243)	−0.283(0.243)	−0.290(0.243)
Current smoker (ref: current non-smoker)	0.198(0.176)	0.192(0.176)	0.197(0.176)
Current drinker (ref: current non-drinker)	−0.026(0.174)	0.006(0.174)	0.001(0.174)
Participate in medical insurance (ref: not participate)	−0.948***(0.206)	−0.836***(0.205)	−0.831***(0.205)
Presence of physical illness (ref: no presence)	6.173***(0.200)	6.135***(0.199)	6.135***(0.199)
Annual household income per household member	−0.702***(0.064)	−0.681***(0.064)	−0.679***(0.064)
Cross-level interactions			
$PM_{2.5}$ × Time spent on physical excises			0.074**(0.036)
$PM_{2.5}$ × The level of reciprocity among neighbors			0.507**(0.221)
$PM_{2.5}$ × Sunny day (ref.: cloudy)			0.049**(0.025)
Constant	15.600***(1.537)	16.024***(1.523)	15.032***(1.677)
Var(Constant)	5.707***	5.416***	5.388***
Var(Residual)	74.411***	73.993***	73.964***
Number of individuals	20,861	20,861	20,861
Number of neighborhoods	158	158	158
AIC	149,491	149,373	149,370

Note: Significance levels:
*$p < .10$, **$p < .05$, ***$p < .01$.

negatively associated with respondents' perception of neighborly reciprocity, probably because individuals living in more polluted areas are less willing to meet and socialize with their neighbors in public spaces, therefore having fewer opportunities to provide instrumental, emotional, and informational assistance to their neighbors (Kim et al., 2010; Lin et al., 2016; Wong et al., 2009). Another finding was that the level of $PM_{2.5}$ was negatively related to respondents' perception of sunlight exposure. Numerous atmospheric studies have suggested that solid particles can reflect and refract sunlight, so residents may perceive less sunlight when the levels of $PM_{2.5}$ are higher (Wang et al., 2012)

Physical activity, neighborly reciprocity, and sunlight exposure were found to be related to the level of depression. Time spent on physical activity was negatively related to respondents' CES-D scores. Regular physical exercise may help ease depression symptoms by releasing endorphins and other natural brain chemicals that can enhance individuals' sense of well-being and by dragging them away from the cycle of negative thoughts (Strawbridge et al., 2002; Teychenne et al., 2008).

Respondents' perception of neighborly reciprocity was negatively related to CES-D scores. Social support has a protective effect against depression directly through interpersonal relationships and indirectly as a buffer against stressful events and circumstances (Cohen and Wills, 1985; Feng et al., 2017; Kawachi et al., 1999; Kawachi et al., 2001; Liu et al., 2017; Maas et al., 2009). Respondents living in supportive neighborhoods are more likely to receive emotional, instrumental, and informational assistance from their neighbors, therefore having a lower risk of depression.

Respondents' perception of sunlight exposure was negatively linked to CES-D scores. Sunshine is important for benefiting hypothalamic suprachiasmatic nuclei and maintaining the normal speed of brain blood flow, both of which influence depression-related physiological processes including sleep cycle, body temperature, blood pressure, and digestion (Benedetti et al., 2001; Kent et al., 2009). Moreover, individuals are less likely to feel anxious and suffer from depression when they are sufficiently exposed to sunlight, as such exposure may raise serotonin levels (Benedetti et al., 2001; Kent et al., 2009).

Table 4
Propensity score matching estimates of the association between the level of $PM_{2.5}$ and CES-D scores.

	Model 5a: *k*-nearest neighbor matching ATT	Model 5b: Radius matching	Model 5c: Kernel matching	Model 5d: Local liner regression matching
Treatment	Coef. (SE)	Coef. (SE)	Coef. (SE)	Coef. (SE)
25%	2.074**(1.036)	2.105**(1.050)	2.092**(1.011)	2.080**(1.035)
50%	3.196**(1.602)	3.147**(1.566)	3.169**(1.525)	3.103**(1.499)
75%	1.017*(0.598)	1.026*(0.603)	1.056*(0.621)	1.041*(0.612)

Note: ATT: average treatment effect on the treated. Significance levels:
*$p < .10$, **$p < .05$, ***$p < .01$.

The results of the cross-level interaction indicated that the level of $PM_{2.5}$ moderated the positive relationship of depression with physical activities, neighborly reciprocity, and exposure to sunlight. $PM_{2.5}$ concentration weakened the protective effect of physical activities on depression, as air pollution may exacerbate neurotoxicity and cause inflammation of the hypothalamus and disrupt the release of anti-depression hormones (e.g., cortisol and testosterone) during physical activities (Buoli et al., 2018; Sinharay et al., 2018). Moreover, $PM_{2.5}$ concentration weakened the protective effect of neighborly reciprocity on depression. Individuals living in supportive neighborhoods may receive less effective support from their neighbors in highly polluted areas, as they are less willing to socialize in public spaces. Lastly, the negative relationship between sunlight exposure and depression was also moderated by the level $PM_{2.5}$. Sunlight exposure is beneficial for maintaining hormone levels, as it can stimulate serotonin systems, the hypothalamus, and the production of melatonin, which all are necessary for controlling the normal level of hormones (Benedetti et al., 2001; Kent et al., 2009). However, $PM_{2.5}$ adversely affects hormone levels by causing inflammation of the hypothalamus and serotonin systems and disrupting the production of melatonin (Kioumourtzoglou et al., 2017).

This study has several limitations. First, like most previous studies (Kent et al., 2009), our study design was cross-sectional, which leads to the issue of reverse causality. Second, as CLDS data did not contain geo-referenced information on neighborhoods, we were not able to take into account the variation of $PM_{2.5}$ concentrations across neighborhoods within a city. While individuals might spend most of their time in their residential neighborhoods, it would be ideal to measure the level of individualized exposure, whereby individuals are tracked along their daily paths (Helbich, 2018; Park and Kwan, 2017). Third, we failed to explore inflammatory pathways linking air pollution to depression because of the lack of relevant data. Finally, the depression scores (CES-D) used in this study were based on self-reported data, which might lead to response bias. Our future work will explore the linkage between air pollution and depression using more reliable data such as diagnostic interview and antidepressant medication data (Helbich et al., 2018).

5. Conclusions

Our findings suggest that individuals who are exposed to higher $PM_{2.5}$ levels are more likely to have depressive symptoms. Further, the association between $PM_{2.5}$ concentration and depressive symptoms was found to be partially mediated by the time spent on outdoor physical activities, the perception of neighborly reciprocity, and exposure to sunlight. The level of $PM_{2.5}$ moderated the relationship of depression with physical activities, neighborly reciprocity, and exposure to sunlight. Researchers should be careful not to restrict future studies to the direct effects of air pollution on depression only.

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Authors' contributions

Ruoyu Wang and Marco Helbich conceived of the study and wrote the first draft of the manuscript, Ye Liu, Desheng Xue, Yao Yao and Penghua Liu provided statistical analyses. All authors provided critical revisions and editing.

Conflicts of interest

The authors have no conflicts of interest to declare.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jad.2019.02.007.

References

Adjayegbewonyo, K., Kawachi, I., Subramanian, S.V., Avendano, M., 2018. High social trust associated with increased depressive symptoms in a longitudinal South African sample. Soc. Sci. Med. 197, 127–135.

Airborne Fine Particulate Matter and Air Quality Index 2016, 2016. from. http://www.pm25.in/.

An, R., Xiang, X., 2015. Ambient fine particulate matter air pollution and leisure-time physical inactivity among US adults. Public. Health. 129 (12), 1637–1644.

Andersen, Z.J., de Nazelle, A., Mendez, M.A., Garcia-Aymerich, J., Hertel, O., Tjønneland, A., Overvad, K., Raaschounielsen, O., Nieuwenhuijsen, M.J., 2015. A study of the combined effects of physical activity and air pollution on mortality in elderly urban residents: the Danish Diet, Cancer, and Health Cohort. Environ. Health. Persp. 123 (6), 557–563.

Baron, R.M., Kenny, D.A., 1986. The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. J. Pers. Soc. Psychol. 51 (6), 1173–1182.

Benedetti, F., Colombo, C., Barbini, B., Campori, E., Smeraldi, E., 2001. Morning sunlight reduces length of hospitalization in bipolar depression. J. Affect. Disorders. 62 (3), 221–223.

Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. Lancet 360 (9341), 1233–1242.

Buoli, M., Grassi, S., Caldiroli, A., Carnevali, G.S., Mucci, F., Iodice, S., Cantone, L., Pergoli, L., Bollati, V., 2018. Is there a link between air pollution and mental disorders? Environ. Int. 118, 154–168.

Cohen, S., Wills, T.A., 1985. Stress, social support, and the buffering hypothesis. Psychol. Bull. 98, 310–357.

Chan, C.K., Yao, X., 2008. Air pollution in mega cities in China. Atmos. Environ. 42 (1), 1–42.

Chen, X., Zhang, L., Huang, J., Song, F., Zhang, L., Qian, Z., Trevathan, E., Mao, H., Han, B., Vaughn, M., Chen, K., Liu, Y., Chen, J., Zhao, B., Jiang, G., Gu, Q., Bai, Z., Dong, G., Tang, N.., 2016. Long-term exposure to urban air pollution and lung cancer mortality: a 12-year cohort study in Northern China. Sci. Total Environ. 571, 855–861.

Chen, S., Oliva, P., Zhang, P., 2018. Air pollution and mental health: evidence from china: national bureau of economic research. Retrieved from. http://www.nber.org/papers/w24686.pdf.

China Labor-force Dynamics Survey, 2016. 2016. from. http://css.sysu.edu.cn/Data.

Cho, J., Choi, Y.J., Suh, M., Sohn, J., Kim, H., Cho, S.-K., Ha, K.H., Kim, C., Shin, D.C., 2014. Air pollution as a risk factor for depressive episode in patients with cardiovascular disease, diabetes mellitus, or asthma. J. Affect. Disord. 157, 45–51.

Chuang, K.J., Chan, C.C., Su, T.C., Lee, C.T., Tang, C.S., 2007. The effect of urban air pollution on inflammation, oxidative stress, coagulation, and autonomic dysfunction in young adults. American J. Resp. Crit. Care Med. 176 (4), 370–376.

Dehejia, R.H., Wahba, S., 2002. Propensity score-matching methods for nonexperimental causal studies. Rev. Econ. Stat. 84 (1), 151–161.

Kooy, Der, G., K., Van Hout, H.P., Van Marwijk, H.W., Marten, H., Stehouwer, C.D., Beekman, A.T., 2007. Depression and the risk for cardiovascular diseases: systematic review and meta analysis. Int. J. Geriatr. Psych. 22 (7), 613–626.

Dong, G., Zhang, P., Sun, B., Zhang, L., Chen, X., Ma, N., Yu, F., Guo, H., Huang, H., Lee, Y., Tang, N., Chen, J., 2012. Long-term exposure to ambient air pollution and respiratory disease mortality in Shenyang, China: a 12-year population-based retrospective cohort study. Respiration 84 (5), 360–368.

Dong, G., Qian, Z., Wang, J., Chen, W., Ma, W., Trevathan, E., Xaverius, P.K., DeClue, R., Wiese, A., Langston, M., Liu, M., Wang, D., Ren, W., 2013a. Association between ambient air pollution and prevalence of stroke and cardiovascular diseases in 33 Chinese communities. Atmosp. Environ. 77, 968–973.

Dong, G., Qian, Z., Xaverius, P.K., Trevathan, E., Maalouf, S., Parker, J., Yang, L., Liu, M., Wang, D., Ren, W., Ma, W., Wang, J., Zelicoff, A., Fu, Q., Simckes, M., 2013b. Association between long-term air pollution and increased blood pressure and hypertension in China. Hypertension 61 (3), 578–584.

Fan, Y., Das, K.V., Chen, Q., 2011. Neighborhood green, social support, physical activity, and stress: assessing the cumulative impact. Health. Place. 17 (6), 1202–1211.

Farrokhi, F., Abedi, N., Beyene, J., Kurdyak, P., Jassal, S.V., 2014. Association between depression and mortality in patients receiving long-term dialysis: a systematic review and meta-analysis. Am. J. Kidney. Dis. 63 (4), 623–635.

Feng, Z., Falkingham, J., Liu, X., Vlachantoni, A., 2017. Changes in living arrangements

and mortality among older people in China. SSM-Popul. Health. 3, 9–19.
Giles, L.V., Koehle, M.S., 2014. The health effects of exercising in air pollution. Sport. Med 44 (2), 223–249.
Goldstein, H., 2011. Multilevel Statistical Models. Arnold, London.
Groenewegen, P.P., Zock, J.P., Spreeuwenberg, P., Helbich, M., Hoek, G., Ruijsbroek, A., Strak, M., Verheij, R.A., Volker, B., Waverijn, G., Dijst, M., 2018. Neighbourhood social and physical environment and general practitioner assessed morbidity. Health. Place. 49, 68–84.
Hare, D.L., Toukhsati, S.R., Johansson, P., Jaarsma, T., 2014. Depression and cardiovascular disease: a clinical review. Eur. Heart. J. 35 (21), 1365–1372.
Helbich, M., 2018. Toward dynamic urban environmental exposure assessments in mental health research. Environ. Res. 161, 129–135.
Helbich, M., Klein, N., Roberts, H., Hagedoorn, P., Groenewegen, P.P., 2018. More green space is related to less antidepressant prescription rates in the Netherlands: A Bayesian geoadditive quantile regression approach. Environl. Res. 166, 290–297.
Hwa-Lung, Y., Chih-Hsin, W., 2010. Retrospective prediction of intraurban spatiotemporal distribution of PM2. 5 in Taipei. Atmos. Environ. 44 (25), 3053–3065.
Kawachi, I., Kennedy, B.P., Glass, R., 1999. Social capital and self-rated health: a contextual analysis. Am. J. Public Health 89 (8), 1187–1193.
Kawachi, I., Berkman, L.F., 2001. Social ties and mental health. J. Urban Health-Bull. NY Acad. Med. 78, 458–467.
Kent, S.T., McClure, L.A., Crosson, W.L., Arnett, D.K., Wadley, V.G., Sathiakumar, N., 2009. Effect of sunlight exposure on cognitive function among depressed and nondepressed participants: a REGARDS cross-sectional study. Environ. Health. 8 (1), 34–43.
Kim, C., Jung, S.H., Kang, D.R., Kim, H.C., Moon, K.T., Hur, N.W., Shin, D.C., Suh, I., 2010. Ambient particulate matter as a risk factor for suicide. Am. J. Psychiat. 167 (9), 1100–1107.
Kioumourtzoglou, M.-A., Power, M.C., Hart, J.E., Okereke, O.I., Coull, B.A., Laden, F., Weisskopf, M.G., 2017. The association between air pollution and onset of depression among middle-aged and older women. Am. J. Epidemiol. 185 (9), 801–809.
Li, F., Liu, Y., Lü, J., Liang, L., Harmer, P., 2014. Ambient air pollution in China poses a multifaceted health threat to outdoor physical activity. J. Epidemiol. Commun. H. 69 (3), 201–204.
Lim, Y.H., Kim, H., Kim, J.H., Bae, S., Park, H.Y., Hong, Y.C., 2012. Air pollution and symptoms of depression in elderly adults. Environ. Health. Persp. 120 (7), 1023–1028.
Lin, G.Z., Li, L., Song, Y.F., Zhou, Y.X., Shen, S.Q., Ou, C.Q., 2016. The impact of ambient air pollution on suicide mortality: a case-crossover study in Guangzhou, China. Environ. Health. 15 (1), 90–97.
Liu, Y., Zhang, F., Liu, Y., Li, Z., Wu, F., 2017. The effect of neighbourhood social ties on migrants' subjective wellbeing in Chinese cities. Habitat. Int. 66, 86–94.
Maas, J., Dillen, S.M.E.V., Verheij, R.A., Groenewegen, P.P., 2009. Social contacts as a possible mechanism behind the relation between green space and health. Health. Place. 15 (2), 586–595.
McCreanor, J., Cullinan, P., Nieuwenhuijsen, M.J., Stewart-Evans, J., Malliarou, E., Jarup, L., Harrington, R., Svartengren, M., Han, L., Ohmanstrickland, P., Chung, K.F., Zhang, J.F., 2007. Respiratory effects of exposure to diesel traffic in persons with asthma. New. Engl. J. Med. 357 (23), 2348–2358.
Mills, N.L., Törnqvist, H., Gonzalez, M.C., Vink, E., Robinson, S.D., Söderberg, S., Boon, N.A., Donaldson, K., Sandstrom, T., Blomberg, A., Newby, D.E., 2007. Ischemic and thrombotic effects of dilute diesel-exhaust inhalation in men with coronary heart disease. New. Engl. J. Med. 357 (11), 1075–1082.
Moussavi, S., Chatterji, S., Verdes, E., Tandon, A., Patel, V., Ustun, B., 2007. Depression, chronic diseases, and decrements in health: results from the World Health Surveys. Lancet 370 (9590), 851–858.
Murray, C.J.L., Vos, T., Lozano, R., Naghavi, M., Flaxman, A.D., Michaud, C., Ezzati, M., Shibuya, K., Salomon, J.A., Abdalla, S., et al., 2012. . Disability-adjusted life years (DALYs) for 291 diseases and injuries in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380 (9859), 2197–2223.
Naarding, P., Schoevers, R.A., Janzing, J.G., Jonker, C., Koudstaal, P.J., Beekman, A.T., 2005. A study on symptom profiles of late-life depression: the influence of vascular, degenerative and inflammatory risk-indicators. J. Affect. Disord. 88 (2), 155–162.
Nel, A., 2005. Air pollution-related illness: effects of particles. Science 308 (5723), 804–806.
Ng, F., Berk, M., Dean, O., Bush, A.I., 2008. Oxidative stress in psychiatric disorders: evidence base and therapeutic implications. Int. J. Neuropsychoph. 11 (6), 851–876.
Ni, Y., Tein, J.-Y., Zhang, M., Yang, Y., Wu, G., 2017. Changes in depression among older adults in China: a latent transition analysis. J. Affect. Disord. 209, 3–9.
Park, Y.M., Kwan, M.P., 2017. Individual exposure estimates may be erroneous when spatiotemporal variability of air pollution and human mobility are ignored. Health. Place. 43, 85–94.
Pimpin, L., Retat, L., Fecht, D., de Preux, L., Sassi, F., Gulliver, J., Belloni, A., Ferguson, B., Corbould, E., Jaccard, A., et al., 2018. . Estimating the costs of air pollution to the National Health Service and social care: an assessment and forecast up to 2035. PLoS. Med. 15 (7), e1002602.
Pinquart, M., Duberstein, P.R., 2010. Depression and cancer mortality: a meta-analysis. Psychol. Med. 40 (11), 1797–1810.
Pope 3rd, , A., C., Hansen, M.L., Long, R.W., Nielsen, K.R., Eatough, N.L., Wilson, W.E., Eatough, D.J., 2004. Ambient particulate air pollution, heart rate variability, and blood markers of inflammation in a panel of elderly subjects. Environ. Health Perspect. 112 (3), 339.
Preacher, K.J., Hayes, A.F., 2008. Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. Behav. Res. Methods 40 (3), 879–891.
Pun, V.C., Manjourides, J., Suh, H., 2017. Association of ambient air pollution with depressive and anxiety symptoms in older adults: results from the NSHAP study. Environ. Health Perspect. 125, 342–348.
Psaltopoulou, T., Sergentanis, T.N., Panagiotakos, D.B., Sergentanis, I.N., Kosti, R., Scarmeas, N., 2013. Mediterranean diet, stroke, cognitive impairment, and depression: a meta-analysis. Ann. Neurol. 74 (4), 580–591.
Radloff, L.S., 1977. The CES-D scale a self-report depression scale for research in the general population. Appl. Psychol. Meas. 1 (3), 385–401.
Roberts, J.D., Voss, J.D., Knight, B., 2014. The association of ambient air pollution and physical inactivity in the United States. PLoS One 9 (3), e90143.
Rosenbaum, P.R., Rubin, D.B., 1983. The central role of the propensity score in observational studies for causal effects. Biometrika 70 (1), 41–55.
Rubin, D.B., Thomas, N., 2000. Combining propensity score matching with additional adjustments for prognostic covariates. J. Am. Stat. Assoc. 95 (450), 573–585.
Rumsfeld, J.S., Ho, P.M., 2005. Depression and cardiovascular disease: a call for recognition. Circulation 111 (3), 250–253.
Ruo, B., Rumsfeld, J.S., Hlatky, M.A., Liu, H., Browner, W.S., Whooley, M.A., 2003. Depressive symptoms and health-related quality of life: the heart and soul study. Jama 290 (2), 215–221.
Seaton, A., Godden, D., MacNee, W., Donaldson, K., 1995. Particulate air pollution and acute health effects. Lancet 345 (8943), 176–178.
Sinharay, R., Gong, J., Barratt, B., Ohman-Strickland, P., Ernst, S., Kelly, F.J., Zhang, J., Collins, P.L., Cullinan, P., Chung, K.F., 2018. Respiratory and cardiovascular responses to walking down a traffic-polluted road compared with walking in a traffic-free area in participants aged 60 years and older with chronic lung or heart disease and age-matched healthy controls: a randomised, crossover study. Lancet 391 (10118), 339–349.
Sobel, M.E., 1982. Asymptotic confidence intervals for indirect effects in structural equation models. Soc. Methodol. 13 (13), 290–312.
Stewart, W.F., Ricci, J.A., Chee, E., Hahn, S.R., Morganstein, D., 2003. Cost of lost productive work time among US workers with depression. JAMA 289 (23), 3135–3144.
Strawbridge, W.J., Deleger, S., Roberts, R., Kaplan, G.A., 2002. Physical activity reduces the risk of subsequent depression for older adults. Am. J. Epidemiol. 156 (4), 328–334.
Szyszkowicz, M., 2007. Air pollution and emergency department visits for depression in Edmonton, Canada. Int. J. Occup. Med. Env. 20 (3), 241–245.
Szyszkowicz, M., Rowe, B., Colman, I., 2009. Air pollution and daily emergency department visits for depression. Int. J. Occup. Med. Env. 22 (4), 355–362.
Tian, T., Chen, Y., Zhu, J., Liu, P., 2015. Effect of air pollution and rural-urban difference on mental health of the elderly in China. Iran. J. Public. Health. 44 (8), 1084.
Teychenne, M., Ball, K., Salmon, J., 2008. Physical activity and likelihood of depression in adults: a review. Prev. Med. 46 (5), 397–411.
Vos, T., Allen, C., Arora, M., Barber, R.M., Bhutta, Z.A., Brown, A., Carter, A., Casey, D.C., Charlson, F.J., Chen, A.Z., et al., 2016. Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. Lancet 388 (10053), 1545–1602.
Wang, R., Xue, D., Liu, Y., Chen, H., Qiu, Y., 2018a. The relationship between urbanization and depression in China: the mediating role of neighborhood social capital. Int. J. Equity. Health. 17 (1), 105–114.
Wang, R., Xue, D., Liu, Y., Liu, P., Chen, H., 2018b. The relationship between air pollution and depression in china: is neighbourhood social capital protective? Int. J. Env. Res. Pub. Heal. 15 (6), 1160–1172.
Wang, Y., Yang, Y., Zhao, N., Liu, C., Wang, Q., 2012. The magnitude of the effect of air pollution on sunshine hours in China. J. Geophys. Res. 117 (D21).
Wang, Y., Eliot, M.N., Koutrakis, P., Gryparis, A., Schwartz, J.D., Coull, B.A., Mittleman, M.A., Milberg, W.P., Lipsitz, L.A., Wellenius, G.A., 2014. Ambient air pollution and depressive symptoms in older adults: results from the MOBILIZE Boston study. Environ. Health. Persp. 122 (6), 553–558.
Wen, X., Balluz, L.S., Shire, J.D., Mokdad, A.H., Kohl III, H.W., 2009. Association of self-reported leisure-time physical inactivity with particulate matter 2.5 air pollution. J. Environ. Health. 72 (1), 40–44.
Wong, C.M., Yang, L., Thach, T.Q., Chau, P.Y.K., Chan, K.P., Thomas, G.N., Lam, T.H., Wong, T.W., Hedley, A.J., Peiris, J.M., 2009. Modification by influenza on health effects of air pollution in Hong Kong. Environ. Health. Persp. 117 (2), 248–253.
Xu, X., Gao, J., Gao, J., Chen, Y., 1994. Air pollution and daily mortality in residential areas of Beijing, China. Arch. Environ. Health. 49 (4), 216–222.
Yang, M., Dijst, M., Helbich, M., 2018. Mental health among migrants in Shenzhen, China: does it matter whether the migrant population is defined by hukou than birthplace? Int. J. Env. Res. Pub. Heal. 15 (2671), 1–11.
Yin, H., Pizzol, M., Jacobsen, J.B., Xu, L., 2018. Contingent valuation of health and mood impacts of $PM_{2.5}$ in Beijing, China. Sci. Total. Environ. 630, 1269–1282.
Yu, H., An, R., Andrade, F., 2017a. Ambient fine particulate matter air pollution and physical activity: a longitudinal study of university retirees in Beijing, China. Am. J. Health. Behav. 41 (4), 401–410.
Yu, H., Yu, M., Gordon, S.P., Zhang, R., 2017b. The association between ambient fine particulate air pollution and physical activity: a cohort study of university students living in Beijing. Int. J. Behav. Nutr. Phy. 14 (1), 136–145.
Zhang, J., Li, N., Tu, X.M., Xiao, S., Jia, C., 2011. Risk factors for rural young suicide in China: a case-control study. J Affect. Disord. 129 (1–3), 244–251.
Zhang, X., Zhang, X., Chen, X., 2017. Happiness in the air: How does a dirty sky affect mental health and subjective well-being? J. Environ. Econ. Manage 85, 81–94.
Zhang, X., Chen, X., Zhang, X., 2018. The impact of exposure to air pollution on cognitive performance. Proc Natl Acad Sci USA 115, 9193–9197.
Zich, J., Attkisson, C.C., Greenfield, T.K., 1990. Screening for depression in primary care clinics: the CES-D and the BDI. Int. J. Psychiat. Med. 20 (3), 259–277.