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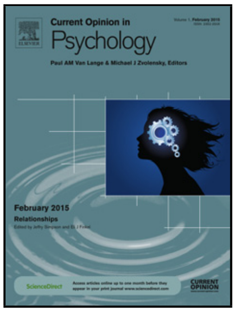

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Air Pollution: A Systematic Review of Its Psychological, Economic, and Social Effects

Forthcoming in *Current Opinion in Psychology*

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Abstract

This review (178 published articles) is the first to systematically examine the psychological (affective, cognitive, behavioral), economic, and social effects of air pollution *beyond* its physiological and environmental effects. Affectively, air pollution decreases happiness and life satisfaction, and increases annoyance, anxiety, mental disorders, self-harm, and suicide. Cognitively, it impairs cognitive functioning and decision making. Behaviorally, air pollution triggers avoidance behavior, defensive expenditure, and migration as coping strategies. Economically, it hurts work productivity and stock markets. Socially, it worsens criminal activities and perceptions of the government. Importantly, both actual and perceived air pollution levels matter. Limitations of past research and future directions are discussed.

Keywords: Air Pollution; Review; Psychology; Economics; Affect; Cognition; Behavior

Air Pollution: A Systematic Review of Its Psychological, Economic, and Social Effects

Air pollution is a grave problem that impacts billions of people across the globe. For example, it is the primary cause of death in India, killing over 1.6 million people a year [1].

According to the Environmental Protection Agency (EPA), in 2017 about 111 million Americans (about 35% of the U.S. population) were living in counties with unhealthy air [2]. Along with the rise of social ecology, social science research on air pollution has been proliferating in recent decades. However, there has yet to be a systematic review of its psychological (affective, cognitive, behavioral), economic, and social effects beyond its physiological and environmental effects.

The present review surveyed 178 published papers in English. The literature search was conducted in the following databases: Google Scholar, PsycINFO, ProQuest, PubMed, Science Direct, Scopus, and Web of Science. Moreover, the corresponding authors of these papers were contacted to ensure that no relevant or unpublished papers had been overlooked. Table 1 presents the papers by category, outcome, and year. Importantly, it details both the pollutants measured and the pollutants found to have a significant effect.

Air pollution is a mixture of particulate matter (e.g., $PM_{2.5}$, PM_{10}), gases (e.g., carbon monoxide [CO], nitrogen dioxide [NO_2], ozone [O_3], sulfur dioxide [SO_2]), organic compounds (e.g., polycyclic aromatic hydrocarbon [PAH]), and metals (e.g., lead). Composite measures include the air pollution index (API) and air quality index (AQI). As shown in Table 1, $PM_{2.5}$ and PM_{10} were the most widely studied pollutants.

Psychological Effects

Happiness and Life Satisfaction (Subjective Well-Being)

A wealth of research shows that air pollution negatively predicts people's happiness and life satisfaction. This effect has been observed across the world, including Australia [3], Canada [4], China [5–10], USA [11], and Europe [12–23]. While most studies relied on self-report measures of happiness and life satisfaction, recent research has begun to leverage unobtrusive social media data. For example, through an analysis of 210 million geotagged Weibo tweets in China, Zheng and colleagues [10] revealed that air pollution was associated with lower happiness expressed in tweets. Importantly, analyzing data from 48 countries (1990-2006), Menz [24] estimated that people's life satisfaction generally does not habituate to air pollution over time.

Annoyance, Anxiety, Mental Disorders, Self-Harm, and Suicide

Air pollution is also associated with increased annoyance [25–29] and anxiety [30–38]. For example, in an assessment of 71,271 elderly women, Power and colleagues [33] found that exposure to $PM_{2.5}$—especially recent exposure—predicted increased anxiety symptoms. Physiologically, exposure to air pollution can trigger anxiety by increasing oxidative stress and systemic inflammation [39]. Psychologically, perceived air pollution can trigger existential anxiety about one's health and future [38].

More devastatingly, air pollution is associated with increased mental disorders, such as depression [7,34,35,40–55], schizophrenia [56,57], and autism [58–65]. In addition to self-report measures of depression [7,34,35,49–55], several studies have leveraged objective measures from hospitals [40–48]. In a series of studies, Szyszkowicz and colleagues found that there tended to be more emergency department visits for depression on more polluted days [40–43,46].

Even worse, air pollution may be a risk factor for substance abuse [66], non-suicidal self-harm [67], and suicide [68–79]. Notably, the effects of air pollution on suicide were found to be stronger for men than for women [67,69,70,72,74–76].

Cognitive Functioning

Besides its negative effects on affective well-being, air pollution also harms cognitive functioning across all life stages, from prenatal development [80–91], childhood and youth [88,92–107], to young and old adults [108–122]. The impacted cognitive outcomes include attention, visuo-construction, memory, math ability, reading comprehension, verbal intelligence, and non-verbal intelligence. For example, Ebenstein and colleagues [98], by exploiting variation across the same students taking multiple matriculation exams, found that contemporaneous $PM_{2.5}$ exposure negatively predicted performance; remarkably, $PM_{2.5}$ exposure during these exams also negatively predicted post-secondary educational attainment and earnings in the long run. Using a nationally representative longitudinal dataset from China, Zhang and colleagues [113] found that, controlling for contemporaneous exposure, cumulative exposure to air pollution impeded cognitive performance in standardized math and verbal tests. More seriously, air pollution may lead to cognitive disorders like dementia and attention deficit hyperactivity disorder [59,60,123–129]. For example, Cacciottolo and colleagues [127] found that living in places with $PM_{2.5}$ exceeding EPA standards increased the risk for dementia by 92%. Again, several of these studies found that the harmful effects of air pollution on human cognition were worse for men than for women [94,97–99,113].

Decision Making

In light of the negative effects of air pollution on cognitive performance, it is unsurprising that air pollution impairs decision-making quality [130]. For example, professional baseball umpires were more likely to make incorrect calls when ambient CO and $PM_{2.5}$ were at high levels [131]. In addition to reducing decision *quality*, air pollution may alter decision-making *tendencies*. For example, Chew and colleagues [132] found that on highly polluted days, individuals exhibited increased risk aversion, ambiguity aversion, and impatience in temporal decision making. A recent study [133] found that air pollution exacerbated the disposition bias, or investors' tendency to sell winning assets while retaining failing assets.

Avoidance Behavior, Defensive Expenditure, and Migration

Behaviorally, people react to air pollution in several ways. First, when air pollution is high, people tend to avoid outdoor activities [134–138] such as cycling [139], zoo and observatory attendance [140], park usage [141], and school attendance [142–144].

Second, air pollution increases defensive expenditure, with individuals spending more on facemasks [145,146], air purifiers [145,147], and health insurance [148]. For example, Zhang and Mu [146] found that in China a 100-point increase in AQI increased the consumption of all masks by 54.5% and anti-$PM_{2.5}$ masks by 70.6%. Using transaction-level data from a Chinese insurance company, Chang and colleagues [148] found that a one-standard-deviation increase in daily air pollution led to a 7.2% increase in the number of health insurance contracts purchased that day. Interestingly, a one-standard-deviation decrease in air pollution from the purchase date increased the probability of cancellation during the cost-free period by 4.0%.

Third, residents in polluted regions show increased interest in emigration. A study on air pollution in the capital region of China (Beijing-Tianjin-Hebei) found that perceived physical health risk, mental health risk, and government control predicted skilled workers' migration intention [149]. Moreover, Qin and Zhu [150] found that a 100-point increase in AQI predicted a 2.3%-4.8% increase in internet searches for "emigration" the next day.

Economic Effects

Work Productivity

Related to the negative effects of air pollution on affective well-being and cognitive functioning, a growing body of work suggests that air pollution can reduce work productivity in two ways. First, air pollution decreases labor supply by increasing *absenteeism* [151–155]. For example, Aragón and colleagues [154] found that moderate levels of $PM_{2.5}$ reduced the working hours of adults, likely because of their need to care for susceptible dependents (e.g., small children and elderly adults). Second, air pollution decreases productivity at work by increasing *presenteeism* [156–159]. For example, Graff Zivin and Neidell [156] found that a 10-ppb increase in ozone decreased the productivity of outdoor crop harvest workers by 5.5%. Similarly, studying the largest call center in China, Chang and colleagues [158] found that a 10-unit increase in API decreased the number of daily calls handled by a worker by 0.35% on average.

Stock Markets

Mounting evidence suggests that air pollution hurts stock markets. In their examination of four U.S. stock exchanges, Levy and Yagil [160] found that air pollution negatively predicted stock returns; this effect was weaker the more distant air pollution was from a stock exchange. Similar findings have been observed in stock exchanges in China [161,162], Italy [163], Turkey [164], Canada, the Netherlands, and Australia [165].

Social Effects

Crime and Unethical Behavior

An extensive body of research demonstrates that air pollution is associated with increased criminal and unethical behavior [38,166–177]. For example, analyzing a 9-year panel of 9,360 U.S. cities, Lu and colleagues [38] found that air pollution predicted both violent crimes (murder, rape, robbery, assault) and property crimes (burglary, motor vehicle theft). Similarly, Bondy and colleagues [169] provided quasi-experimental evidence for the effects of air pollution on both violent and property crimes in London by exploiting daily wind direction as an exogenous source of random variation in air pollution.

Regarding the mechanism, evidence suggests that the psychological experience of air pollution can increase unethical behavior by elevating anxiety, possibly because the induced anxiety depletes individuals' self-control and narrows their focus on their own interests rather than moral principles [38,177–179]. Consistent with these findings, Chew and colleagues [132] found that on days of high air pollution, individuals were more selfish and less prosocial (e.g., giving less in a dictator game, contributing less in a public goods game, reciprocating less in a sequential prisoner’s dilemma, demanding more in an ultimatum game).

Perception of the Government

Because the government plays an important role in regulating air pollution, it is plausible that citizens would have a negative perception of the government on highly polluted days. For example, Shi and Guo [180] found that pollution levels predicted more online searches for the word “corruption”. Likewise, Huang and colleagues [181] provided experimental evidence for the psychological experience of air pollution on perceived corruption: When individuals recalled hazy (vs. cloudy) days, they were more likely to perceive the government as corrupt.

Limitations of Past Research and Future Directions

Data vs. Theory Driven

One limitation of past research is that many studies on air pollution were data driven rather than theory driven. Researchers tend to collect data on all pollutants accessible without specifying *a priori* which pollutants would influence the outcome variable(s). As a result, it is common to read sentences like “pollutant X, but not pollutant Y, had a significant effect”. Similarly, although the detrimental effects of air pollution are consistent across studies, estimates of magnitude vary considerably. To achieve greater theoretical and empirical precision, future research could benefit from two practices. First, pre-registering the hypothesized results could reduce Type I error and the file-drawer problem. Second, understanding how pollutants differ (e.g., in size, color, odor, physiological effects) can inform *why* some pollutants but not others should influence a given outcome. For example, small pollutants (e.g., $PM_{2.5}$) can travel indoors and thus affect indoor work productivity, whereas large pollutants cannot [157]. Likewise, colored and malodorous pollutants (e.g., NO_2) may influence *perceived* pollution more strongly than colorless and odorless pollutants.

Actual vs. Perceived Air Pollution

Relatedly, for the varied outcomes reviewed above, it is often unclear whether the effect of air pollution is more physiological or psychological. To date, only a small percentage of studies have assessed both actual and perceived pollution levels [29,139,140,149,182]. These studies suggest that the *perception* of air pollution levels matters. For example, Neidell [140] found that zoo attendance dropped by 13% and observatory attendance dropped by 6% when a smog alert was issued relative to days with similar levels of air pollution but no smog alert. Similarly, Fehr and colleagues [177] found that employees' *perception* of air pollution levels—but not actual air pollution levels—predicted their unethical behavior at work. To ascertain whether the effect of air pollution on a given outcome is more psychological or physiological, future studies should measure both actual and perceived pollution levels and assess the effects of one while controlling for the other.

Conclusion

Research on the psychological, economic, and social effects of air pollution is booming. Air pollution corrupts not only the health of individuals, but also the health of society.

Conflict of interest: None declared.

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Table 1
Published Studies on the Psychological, Economic, and Social Effects of Air Pollution

Category	**Outcome**	**Author(s), Year**	**Pollutants Measured**	**Pollutants with Significant Effects**	**Location**
PSYCHOLOGICAL (Affective)	**Happiness & Life Satisfaction**	Welsch, 2006	NO_2, Pb, TSP	NO_2, Pb	10 European countries
		Di Tella & MacCulloch, 2008	SOx	SOx	12 OECD countries
		Rehdanz & Maddison, 2008	Perceived pollution	Perceived pollution	Germany
		Smyth et al., 2008	SO_2	SO_2	China (30 cities)
		Luechinger, 2009	SO_2	SO_2	Germany (445 counties)
		MacKerron & Mourato, 2009	NO_2, PM_{10}, perceived pollution	NO_2, PM_{10}, perceived pollution	UK (London)
		Ferreira & Moro, 2010	PM_{10}	PM_{10}	Ireland
		Menz, 2011	PM_{10}	PM_{10}	48 countries
		Levinson, 2012	PM_{10}	PM_{10}	USA (10,193 counties)
		Menz & Welsch, 2012	NO_2, SO_2	NO_2, SO_2	10 European countries
		Ferreira et al., 2013	SO_2	SO_2	23 European countries (248 regions)
		Ambrey et al., 2014	PM_{10}	PM_{10}	Australia (South East Queensland)
		Dolan & Laffan, 2016	$PM_{2.5}$	$PM_{2.5}$	UK
		Giovanis & Ozdamar, 2016	CO, NO_2, O_3, PM_{10}, SO_2	CO, NO_2, O_3, PM_{10}, SO_2	Switzerland
		Orru et al., 2016	PM_{10}	PM_{10}	Estonia
		Xu & Li, 2016	Perceived pollution	Perceived pollution	China
		Barrington-Leigh & Behzadnejad, 2017	CO, NO_2, $PM_{2.5}$, SO_2	SO_2	Canada
		Ozdamar & Giovanis, 2017	CO, NO_x, O_3,	NO_x, O_3	UK
		Zhang, Zhang, & Chen, 2017a	API (NO_2, PM_{10}, SO_2)	API (NO_2, PM_{10}, SO_2)	China (162 counties)
		Zhang, Zhang, & Chen, 2017b	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	$PM_{2.5}$	China (162 counties)
		Yuan et al., 2018	AQI	AQI	China (281 cities)

		Zheng et al., 2019	AQI, $PM_{2.5}$	AQI, $PM_{2.5}$	China (144 cities)
	Annoyance & Anxiety	Rotko et al., 2002	NO_2, $PM_{2.5}$	NO_2, $PM_{2.5}$	Athens, Basel, Milan, Oxford, Prague, Helsinki
		Jacquemin et al., 2007	$PM_{2.5}$, S	$PM_{2.5}$, S	12 European countries (25 centers)
		Modig & Forsberg, 2007	NO_2	NO_2	Sweden (Umeå; Uppsala; Gothenburg)
		Llop et al., 2008	NO_2	NO_2	Spain (Valencia)
		Heaney et al., 2011	H_2S from landfill	H_2S from landfill	USA (Orange County, North Carolina)
		Claeson et al., 2013	Perceived pollution, odorants	Perceived pollution	Sweden (Värnamo)
		Cho et al., 2015	CO, NO_2, O_3, PM_{10}, SO_2	O_3	South Korea (Seoul)
		Mehta et al., 2015	Black carbon, NO_2, O_3, $PM_{2.5}$, particle number counts, SO_4^{2-}	Black carbon, NO_2, $PM_{2.5}$, particle number counts	USA (Greater Boston area, Massachusetts)
		Power et al., 2015	$PM_{2.5}$, $PM_{2.5-10}$	$PM_{2.5}$	USA (48 continental states)
		Lin, Zhou, et al., 2017	NO_2, PM_{10}, SO_2	NO_2, PM_{10}, SO_2	China (Shanghai)
		Pun et al., 2017	$PM_{2.5}$	$PM_{2.5}$	USA
		Sass et al., 2017	$PM_{2.5}$	$PM_{2.5}$	USA
		Vert et al., 2017	NO_2, NO_x, $PM_{2.5}$, $PM_{2.5}$ absorbance, PM_{10}, PM_{coarse}	n.s.	Spain (Barcelona)
		Xu et al., 2017	Perceived haze	Perceived haze	China (Nanjing, Jiangsu Province)
		Lu, Lee, et al., 2018	Perceived pollution	Perceived pollution	USA (9,360 cities)
	Mental Disorders	Pedersen et al., 2004	Benzene, CO, NO_x, NO_2	Benzene, CO	Denmark
		Szyszkowicz, 2007	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	Warm season: CO, NO_2, SO_2, O_3; Cold season: $PM_{2.5}$, PM_{10}	Canada (Edmonton, Alberta)

		Szyszkowicz et al., 2009	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	CO, NO_2, PM_{10}, SO_2	Canada (Edmonton; Halifax; Montreal; Ottawa; Toronto; Vancouver)
		Szyszkowicz, 2011	SO_2	SO_2	Canada (Toronto)
		Szyszkowicz & Tremblay, 2011	CO, NO_2, SO_2	NO_2, SO_2	Canada (Edmonton, Alberta)
		Lim et al., 2012	CO, NO_2, O_3, PM_{10}, SO_2	NO_2, O_3, PM_{10}	South Korea (Seoul)
		Becerra et al., 2013	CO, NO, NO_2, O_3, $PM_{2.5}$, PM_{10}	NO, NO_2, O_3, $PM_{2.5}$	USA (Los Angeles)
		Volk et al., 2013	NO_2, O_3, $PM_{2.5}$, PM_{10}, traffic-related pollution	NO_2, $PM_{2.5}$, PM_{10}, traffic-related pollution	USA (California)
		Cho et al., 2014	CO, NO_2, O_3, PM_{10}, SO_2	CO, NO_2, PM_{10}, SO_2	South Korea (Seoul)
		Gong et al., 2014	NO_x, PM_{10}	n.s.	Sweden (Stockholm)
		Kalkbrenner et al., 2015	PM_{10}	PM_{10}	USA (North Carolina; California)
		Raz et al., 2015	$PM_{2.5}$, $PM_{2.5-10}$	$PM_{2.5}$	USA
		Talbott et al., 2015	$PM_{2.5}$	$PM_{2.5}$	USA (southwestern Pennsylvania)
		Kim, Lim, et al., 2016	$PM_{2.5}$	$PM_{2.5}$	South Korea
		Szyszkowicz et al., 2016	NO_2, O_3, $PM_{2.5}$, SO_2	NO_2, O_3, $PM_{2.5}$, SO_2	Canada (9 urban areas in Ontario)
		Zijlema et al., 2016	NO_2, $PM_{2.5}$, $PM_{2.5}$ absorbance, PM_{10}	n.s.	Finland, Germany, Netherlands, Norway
		Gao et al., 2017	CO, NO_2, O_3, $PM_{2.5}$, $PM_{2.5-10}$, PM_{10}, SO_2	$PM_{2.5}$, $PM_{2.5-10}$, PM_{10}	China (Beijing)
		Ha, 2017	$PM_{2.5}$	$PM_{2.5}$	USA (48 contiguous states)
		Kioumourtzoglou et al., 2017	O_3, $PM_{2.5}$	O_3, $PM_{2.5}$	USA (48 continental states)
		Lin, Guo, et al., 2017	$PM_{2.5}$	$PM_{2.5}$	China, Ghana, India, Mexico, Russia, South Africa

		Lin, Zhou, et al., 2017	NO_2, PM_{10}, SO_2	SO_2	China (Shanghai)
		Pun et al., 2017	$PM_{2.5}$	$PM_{2.5}$	USA
		Raz et al., 2018	NO_2	NO_2	Israel (central costal area)
		Vert et al., 2017	NO_2, NO_x, $PM_{2.5}$, $PM_{2.5}$ absorbance, PM_{10}, PM_{coarse}	NO_2, NO_x, $PM_{2.5}$, $PM_{2.5}$ absorbance, PM_{10}	Spain (Barcelona)
		Zhang, Zhang, & Chen, 2017a	API (NO_2, PM_{10}, SO_2)	API (NO_2, PM_{10}, SO_2)	China (162 counties)
		Chen, Liu, et al., 2018	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	CO, PM_{10}, SO_2	China (Shanghai)
		Kerin et al., 2018	NO_2, O_3, $PM_{2.5}$, PM_{10}, near-roadway pollution	NO_2	USA (California)
		Oudin et al., 2018	NO_2, O_3, PM_{10}	PM_{10} (during warm season)	Sweden (Gothenburg)
		Shin et al., 2018	CO, NO_2, PM_{10}, SO_2	CO, NO_2, PM_{10}	South Korea
		Wang et al., 2018	$PM_{2.5}$	$PM_{2.5}$	China (158 prefectures)
	Self-Harm & Suicide	Biermann et al., 2009	O_3	O_3	Germany (Middle Franconia, Bavaria)
		Kim, Jung, et al., 2010	$PM_{2.5}$, PM_{10}	$PM_{2.5}$, PM_{10}	South Korea (Seoul; Busan; Incheon; Daejeon; Daegu; Gwangju; Ulsan)
		Szyszkowicz et al., 2010	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	CO, NO_2, $PM_{2.5}$, PM_{10}, SO_2 (for cold period)	Canada (Vancouver)
		Yang et al., 2011	CO, NO_x, O_3, PM_{10}, SO_2	CO, O_3, PM_{10}, SO_2	Taipei City
		Bakian et al., 2015	NO_2, $PM_{2.5}$, PM_{10}, SO_2	NO_2, $PM_{2.5}$	USA (Salt Lake County, Utah)
		Kim, Myung, et al., 2015	CO, NO_2, O_3, PM_{10}, SO_2	O_3, PM_{10}	South Korea (16 administrative regions)
		Lin et al., 2016	NO_2, PM_{10}, SO_2	NO_2, PM_{10}, SO_2 (cool seasons only)	China (Guangzhou, Guangdong Province)
		Ng et al., 2016	NO_2, $PM_{2.5}$, SO_2, SPM	NO_2, $PM_{2.5}$, SO_2	Japan (Tokyo)

		Casas et al., 2017	O_3, PM_{10}	O_3, PM_{10}	Belgium
		Liu, Sun, et al., 2018	CO, NO_2, O_3, $PM_{2.5}$, SO_2	CO, O_3, $PM_{2.5}$	China (Jiangsu Province)
		Kim, Ng, et al., 2018	NO_2, $PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10}, SO_2	NO_2, $PM_{2.5\text{-}10}$, PM_{10}, SO_2	10 cities in Northeast Asia
		Lee et al., 2018	CO, NO_2, O_3, PM_{10}, SO_2	CO, NO_2, PM_{10}, SO_2	South Korea (26 cities)
		Min et al., 2018	NO_2, PM_{10}, SO_2	NO_2, PM_{10}, SO_2	South Korea
		Szyszkowicz et al., 2018	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	CO, NO_2, $PM_{2.5}$, PM_{10}	Canada (Edmonton, Alberta)
PSYCHOLOGICAL (Cognitive)	**Cognitive Functioning (prenatal)**	Perera et al., 2006	PAHs	PAHs	USA (New York City, New York)
		Perera et al., 2009	PAHs	PAHs	USA (New York City, New York)
		Edwards et al., 2010	PAHs	PAHs	Poland (Krakow)
		Sanders, 2012	TSP	TSP	USA (Texas)
		Vrijheid et al., 2012	Gas cooking	Gas cooking	Spain
		Guxens et al., 2014	NO_2, NO_x, $PM_{2.5}$, PM_{10}, PM_{coarse}	NO_2, $PM_{2.5}$	France, Germany, Greece, Italy, Netherlands, Spain
		Harris et al., 2015	Black carbon, $PM_{2.5}$, residential proximity to major roadways, near-residence traffic density	Residential proximity to major roadways, near-residence traffic density	USA (Massachusetts)
		Jedrychowski et al., 2015	PAHs	PAHs	Poland (Krakow)
		Lertxundi et al., 2015	NO_2, $PM_{2.5}$, benzene	NO_2, $PM_{2.5}$	Spain (Guipúzcoa)
		Yorifuji et al., 2016	NO_2, SPM, SO_2	NO_2, SPM, SO_2	Japan
		Bharadwaj et al., 2017	AQI (CO, O_3, PM_{10})	AQI (CO, O_3, PM_{10})	Chile (Santiago)
		Isen et al., 2017	TSP	TSP	USA
	Cognitive Functioning (children & youths)	Coscia et al., 2003	Pb	Pb	USA (Cincinnati, Ohio)
		Braun et al., 2006	Pb	Pb	USA
		Pastor et al., 2006	Respiratory hazard ratio	Respiratory hazard ratio	USA (Los Angeles, California)

		Suglia et al., 2008	Black carbon	Black carbon	USA (Boston, Massachusetts)
		Calderón-Garcidueñas et al., 2008	O_3, $PM_{2.5}$, PM_{10}	O_3, $PM_{2.5}$, PM_{10}	Mexico (Mexico City; Polotitlán)
		Tang et al., 2008	Hg, PAHs, Pb	PAHs, Pb	China (Chongqing)
		Froehlich et al., 2009	Pb	Pb	USA
		Morales et al., 2009	NO_2	NO_2	Spain (Menorca)
		Wang et al., 2009	NO_2	NO_2	China (Quanzhou, Fujian Province)
		Freire et al., 2010	NO_2	n.s.	Spain (Granada)
		Mohai et al., 2011	EPA’s Risk-Screening Environmental Indicator	EPA’s Risk-Screening Environmental Indicator	USA (Michigan)
		Siddique et al., 2011	NO_x, PM_{10}, SO_x	PM_{10}	India (Delhi)
		van Kempen et al., 2012	NO_2	NO_2	Netherlands (Amsterdam)
		Chiu et al., 2013	Black carbon	Black carbon	USA (Boston, Massachusetts)
		Harris et al., 2015	Black carbon, $PM_{2.5}$, residential proximity to major roadways, near-residence traffic density	Residential proximity to major roadways, near-residence traffic density	USA (Massachusetts)
		Kicinski et al., 2015	Traffic exposure	Traffic exposure	Belgium (Flanders)
		Stafford, 2015	Indoor air quality	Indoor air quality	USA (Texas)
		Sunyer et al., 2015	Elemental carbon, NO_2, UFP	Elemental carbon, NO_2, UFP	Spain (Barcelona)
		Ebenstein et al., 2016	$PM_{2.5}$	$PM_{2.5}$	Israel
		Min & Min, 2017	NO_2, PM_{10}	NO_2, PM_{10}	South Korea
		Wang et al., 2017	$PM_{2.5}$	$PM_{2.5}$	USA (Los Angeles)
	Cognitive Functioning (young and old adults)	Sun & Gu, 2008	API (CO, NO_2, O_3, PM_{10}, SO_2)	API (CO, NO_2, O_3, PM_{10}, SO_2)	China (171 cities)
		Chen & Schwartz, 2009	O_3, PM_{10}	O_3	USA

		Ranft et al., 2009	PM_{10}, residential distance to the next busy road	Residential distance to the next busy road	Germany (the Ruhr area)
		Zeng et al., 2010	API	API	China (866 counties)
		Power et al., 2011	Black carbon	Black carbon	USA (Greater Boston area, Massachusetts)
		Wellenius et al., 2012	Residential distance to the nearest major roadway	Residential distance to the nearest major roadway	USA (Boston, Massachusetts)
		Weuve et al., 2012	$PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10}	$PM_{2.5}$, $PM_{2.5\text{-}10}$	USA
		Loop et al., 2013	$PM_{2.5}$		USA (48 states)
		Ailshire & Crimmins, 2014	$PM_{2.5}$	$PM_{2.5}$	USA
		Ailshire & Clarke, 2015	$PM_{2.5}$	$PM_{2.5}$	USA
		Gatto et al., 2014	NO_2, O_3, $PM_{2.5}$	$PM_{2.5}$	USA (Los Angeles, California)
		Tonne et al., 2014	$PM_{2.5}$, PM_{10}	$PM_{2.5}$, PM_{10}	UK (London)
		Schikowski et al., 2015	NO_2, NO_x, $PM_{2.5}$, $PM_{2.5}$ absorbance, PM_{10}	NO_2, NO_x, $PM_{2.5}$, $PM_{2.5}$ absorbance, PM_{10}	Germany (Southern Muensterland)
		Kioumourtzoglou et al., 2016	$PM_{2.5}$	$PM_{2.5}$	USA (50 northeastern cities)
		Oudin et al., 2016	NO_x	NO_x	Sweden (Umeå)
		Cacciottolo et al., 2017	$PM_{2.5}$	$PM_{2.5}$	USA (48 states)
		Chen, Kwong, et al., 2017	NO_2, $PM_{2.5}$	NO_2, $PM_{2.5}$	Canada (Ontario)
		Zhang, Chen, & Zhang, 2018	API (NO_2, PM_{10}, SO_2)	API (NO_2, PM_{10}, SO_2)	China (162 counties)
		Heyes, Rivers, & Schaufele, 2019	$PM_{2.5}$	$PM_{2.5}$	Canada (Ottawa)
	Decision Making	Archsmith et al., 2018	CO, O_3, $PM_{2.5}$	CO, $PM_{2.5}$	USA
		Huang et al., 2019	AQI (CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2)	AQI (CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2)	China (34 cities)
		Dong et al., in press	AQI	AQI	China (105 cities)
PSYCHOLOGICAL (Behavioral)	**Avoidance Behavior**	Bresnahan et al., 1997	CO, NO_2, O_3, SO_2	O_3	USA (Los Angeles, California)

		Mansfield et al., 2006	AQI	AQI	USA (35 metropolitan areas)
		Currie et al., 2009	CO, O_3, PM_{10}	CO	USA (Texas)
		Graff Zivin & Neidell, 2009	O_3 alert	O_3 alert	USA (Southern California)
		Neidell, 2009	O_3 alert	O_3 alert	USA (Southern California)
		Wen et al., 2009	AQI alert	AQI alert	USA (Colorado; Florida; Indiana; Kansas; Massachusetts; Wisconsin)
		Moretti & Neidell, 2011	O_3	O_3	USA (Los Angeles, California)
		Noonan, 2014	O_3 alert	O_3 alert	USA (Atlanta, Georgia)
		Hales et al., 2016	$PM_{2.5}$, PM_{10}	$PM_{2.5}$, PM_{10}	USA (Utah)
		Saberian et al., 2017	AQI alert	AQI alert	Australia (Sydney)
		Liu & Salvo, 2018	$PM_{2.5}$	$PM_{2.5}$	China (a major urban center)
	Defensive Expenditure	Sun et al., 2017	$PM_{2.5}$	$PM_{2.5}$	China
		Chang et al., 2018	AQI	AQI	China
		Liu, He, & Lau, 2018	$PM_{2.5}$ alert	$PM_{2.5}$ alert	China (Beijing; Tianjin; Shanghai; Guangzhou; Chengdu; Chongqing; Shenyang; Xi’an)
		Zhang & Mu, 2018	AQI	AQI	China (190 cities)
	Migration	Kahn, 2000	O_3	O_3	USA (California counties)
		Lu, Yue, et al., 2018	Smog risk perception	Smog risk perception	China (Beijing–Tianjin–Hebei region)
		Qin & Zhu, 2018	AQI	AQI	China (153 cities)
ECONOMIC	**Work Productivity (Absenteeism)**	Ostro, 1983	Sulfate, TSP	TSP	USA (84 metropolitan statistical areas)
		Hansen & Selte, 2000	NO_2, PM_{10}, SO_2,	PM_{10}	Norway (Oslo)

		Hanna & Oliva, 2015	SO_2	SO_2	Mexico (Mexico City)
		Aragón et al., 2017	NO_2, $PM_{2.5}$, PM_{10}, SO_2	NO_2, $PM_{2.5}$	Peru (Lima)
		Jans et al., 2018	PM_{10}	PM_{10}	Sweden
	Work Productivity (Presenteeism)	Graff Zivin & Neidell, 2012	O_3	O_3	USA (Central Valley, California)
		Chang et al., 2016	$PM_{2.5}$	$PM_{2.5}$	USA (Northern California)
		Chang et al., 2019	API	API	China (Shanghai; Nantong, Jiangsu Province)
		He, Liu, & Salvo, 2019	$PM_{2.5}$, SO_2	$PM_{2.5}$, SO_2	China (Henan Province; Jiangsu Province)
	Stock Markets	Levy & Yagil, 2011	AQI	AQI	USA (New York; Philadelphia)
		Levy & Yagil, 2013	AQI	AQI	Australia, Canada, China, Netherlands, USA
		Demir & Ersan, 2016	PM_{10}	PM_{10}	Turkey (Istanbul; Ankara; Izmir)
		Lepori, 2016	PM, NO_x, SO_2	PM, NO_x, SO_2	Italy (Milan)
		Li & Peng, 2016	AQI	AQI	China
		He & Liu, 2018	AQI	AQI	China (Shanghai)
SOCIAL	**Crime & Unethical Behavior**	Nevin, 2000	Pb	Pb	USA
		Dietrich et al., 2001	Pb	Pb	USA (Cincinnati, Ohio)
		Stretesky & Lynch, 2001	Pb	Pb	USA (all counties in the contiguous 48 states)
		Needleman et al., 2002	Pb	Pb	USA (Pittsburgh, Pennsylvania)
		Nevin, 2007	Pb	Pb	Australia, Canada, Finland, France, West Germany, Italy, New Zealand, UK, USA
		Reyes, 2007	Pb	Pb	USA (50 states and DC)
		Haynes et al., 2011	Hg, Mn, Pb, $PM_{2.5}$, PM_{10}	Hg, Mn, $PM_{2.5}$, PM_{10}	USA (all 88 Ohio counties)

		Reyes, 2015	Pb	Pb	USA (50 states and DC)
		Fehr et al., 2017	$PM_{2.5}$, perceived pollution	Perceived pollution	China (Wuhan, Hubei Province)
		Lu, Lee, et al., 2018	Composite (CO, NO_2, $PM_{2.5}$, PM_{10}, SO_2, TSP),	Composite (CO, NO_2, $PM_{2.5}$, PM_{10}, SO_2, TSP), perceived pollution	USA (9,360 cities)
		Younan et al., 2018	$PM_{2.5}$	$PM_{2.5}$	USA (Southern California)
		Burkhardt et al., 2019	O_3, $PM_{2.5}$	O_3, $PM_{2.5}$	USA
	Perception of the Government	Huang et al., 2016	NO, N_2O, PM_{10}, SO_2, dust, smoke, perceived pollution	PM_{10}, dust, smoke, perceived pollution	China (36 cities) and 56 countries
		Shi & Guo, 2018	AQI	AQI	China (157 cities)

Pollutant abbreviations: API = air pollution index, AQI = air quality index, CO = carbon monoxide, H_2S = hydrogen sulfide, Hg = mercury, Mn = manganese, NO = nitric oxide, NO_2 = nitrogen dioxide, NO_x = nitrogen oxides, N_2O = nitrous oxide, O_3 = ozone, PAH = polycyclic aromatic hydrocarbons, Pb = lead, PM = particulate matter, PM_{10} = particulate matter with an aerodynamic diameter less than 10µm, $PM_{2.5}$ = particulate matter with an aerodynamic diameter less than 2.5µm, SO_2 = sulphur dioxide, SPM = suspended particulate matter, TSP = total suspended particulate, UFP = ultrafine particulate matter