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Air pollution: A systematic review of its psychological, economic, and social effects

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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 exacerbates criminal activities and worsens perception of the government. Importantly, both actual and perceived air pollution levels matter. Limitations of past research and future directions are discussed.

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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 Moreover, the corresponding authors of these papers were contacted to ensure that no relevant or unpublished papers had been overlooked.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 [5–9,10••], 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 *et al.* [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 [30–37,38•]. For example, in an assessment of 71,271 elderly women, Power *et al.* [33] found that exposure to $PM_{2.5}$ — especially recent exposure — predicted increased anxiety symptoms. Physiologically, exposure to air pollutants 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 [7,34,35,49,41–55], several studies have leveraged

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 and life satisfaction	Welsch [12]	NO_2, Pb, TSP	NO_2, Pb	10 European countries
		Di Tella and MacCulloch [13]	SO_x	SO_x	12 OECD countries
		Rehdanz and Maddison [16]	Perceived pollution	Perceived pollution	Germany
		Smyth *et al.* [5]	SO_2	SO_2	China (30 cities)
		Luechinger [17]	SO_2	SO_2	Germany (445 counties)
		MacKerron and Mourato [18]	NO_2, PM_{10}, perceived pollution	NO_2, PM_{10}, perceived pollution	UK (London)
		Ferreira and Moro [19]	PM_{10}	PM_{10}	Ireland
		Menz [24]	PM_{10}	PM_{10}	48 countries
		Levinson [11]	PM_{10}	PM_{10}	USA (10,193 counties)
		Menz and Welsch [20]	NO_2, SO_2	NO_2, SO_2	10 European countries
		Ferreira *et al.* [21]	SO_2	SO_2	23 European countries (248 regions)
		Ambrey *et al.* [3]	PM_{10}	PM_{10}	Australia (South East Queensland)
		Dolan and Laffan [22]	$PM_{2.5}$	$PM_{2.5}$	UK
		Giovanis and Ozdamar [23]	CO, NO_2, O_3, PM_{10}, SO_2	CO, NO_2, O_3, PM_{10}, SO_2	Switzerland
		Orru *et al.* [14]	PM_{10}	PM_{10}	Estonia
		Xu and Li [6]	Perceived pollution	Perceived pollution	China
		Barrington-Leigh and Behzadnejad [4]	CO, NO_2, $PM_{2.5}$, SO_2	SO_2	Canada
		Ozdamar and Giovanis [15]	CO, NO_x, O_3,	NO_x, O_3	UK
		Zhang *et al.* [7]	API (NO_2, PM_{10}, SO_2)	API (NO_2, PM_{10}, SO_2)	China (162 counties)
		Zhang *et al.* [8]	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	$PM_{2.5}$	China (162 counties)
		Yuan *et al.* [9]	AQI	AQI	China (281 cities)
		Zheng *et al.* [10••]	AQI, $PM_{2.5}$	AQI, $PM_{2.5}$	China (144 cities)
	Annoyance and anxiety	Rotko *et al.* [25]	NO_2, $PM_{2.5}$	NO_2, $PM_{2.5}$	Athens, Basel, Milan, Oxford, Prague, Helsinki
		Jacquemin *et al.* [26]	$PM_{2.5}$, S	$PM_{2.5}$, S	12 European countries (25 centers)
		Modig and Forsberg [27]	NO_2	NO_2	Sweden (Umeå; Uppsala; Gothenburg)
		Llop *et al.* [28]	NO_2	NO_2	Spain (Valencia)
		Heaney *et al.* [30]	H_2S from landfill	H_2S from landfill	USA (Orange County, North Carolina)
		Claeson *et al.* [29]	Perceived pollution, odorants	Perceived pollution	Sweden (Värnamo)
		Cho *et al.* [31]	CO, NO_2, O_3, PM_{10}, SO_2	O_3	South Korea (Seoul)
		Mehta *et al.* [32]	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.* [33]	$PM_{2.5}$, $PM_{2.5\text{-}10}$	$PM_{2.5}$	USA (48 continental states)
		Lin *et al.* [34]	NO_2, PM_{10}, SO_2	NO_2, PM_{10}, SO_2	China (Shanghai)
		Pun *et al.* [35]	$PM_{2.5}$	$PM_{2.5}$	USA
		Sass *et al.* [36]	$PM_{2.5}$	$PM_{2.5}$	USA
		Vert *et al.* [53]	NO_2, NO_x, $PM_{2.5}$, $PM_{2.5}$ absorbance, PM_{10}, PM_{coarse}	n.s.	Spain (Barcelona)

Table 1 (*Continued*)

Category	Outcome	Author(s), year	Pollutants measured	Pollutants with significant effects	Location
		Xu *et al.* [37]	Perceived haze	Perceived haze	China (Nanjing, Jiangsu Province)
		Lu *et al.* [38*]	Perceived pollution	Perceived pollution	USA (9360 cities)
	Mental disorders	Pedersen *et al.* [56]	Benzene, CO, NO_x, NO_2	Benzene, CO	Denmark
		Szyszkowicz [40]	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.* [41]	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 [42]	SO_2	SO_2	Canada (Toronto)
		Szyszkowicz and Tremblay [43]	CO, NO_2, SO_2	NO_2, SO_2	Canada (Edmonton, Alberta)
		Lim *et al.* [49]	CO, NO_2, O_3, PM_{10}, SO_2	NO_2, O_3, PM_{10}	South Korea (Seoul)
		Becerra *et al.* [58]	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.* [59]	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.* [44]	CO, NO_2, O_3, PM_{10}, SO_2	CO, NO_2, PM_{10}, SO_2	South Korea (Seoul)
		Gong *et al.* [60]	NO_x, PM_{10}	n.s.	Sweden (Stockholm)
		Kalkbrenner *et al.* [61]	PM_{10}	PM_{10}	USA (North Carolina; California)
		Raz *et al.* [62]	$PM_{2.5}$, $PM_{2.5\text{-}10}$	$PM_{2.5}$	USA
		Talbott *et al.* [63]	$PM_{2.5}$	$PM_{2.5}$	USA (southwestern Pennsylvania)
		Kim *et al.* [45]	$PM_{2.5}$	$PM_{2.5}$	South Korea
		Szyszkowicz *et al.* [46]	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.* [47]	NO_2, $PM_{2.5}$, $PM_{2.5}$ absorbance, PM_{10}	n.s.	Finland, Germany, Netherlands, Norway
		Gao *et al.* [57]	CO, NO_2, O_3, $PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10}, SO_2	$PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10}	China (Beijing)
		Ha [50]	$PM_{2.5}$	$PM_{2.5}$	USA (48 contiguous states)
		Kioumourtzoglou *et al.* [51]	O_3, $PM_{2.5}$	O_3, $PM_{2.5}$	USA (48 continental states)
		Lin *et al.* [52]	$PM_{2.5}$	$PM_{2.5}$	China, Ghana, India, Mexico, Russia, South Africa
		Lin *et al.* [34]	NO_2, PM_{10}, SO_2	SO_2	China (Shanghai)
		Pun *et al.* [35]	$PM_{2.5}$	$PM_{2.5}$	USA
		Raz *et al.* [65]	NO_2	NO_2	Israel (central costal area)
		Vert *et al.* [53]	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 *et al.* [7]	API (NO_2, PM_{10}, SO_2)	API (NO_2, PM_{10}, SO_2)	China (162 counties)
		Chen *et al.* [48]	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2	CO, PM_{10}, SO_2	China (Shanghai)
		Kerin *et al.* [64]	NO_2, O_3, $PM_{2.5}$, PM_{10}, near-roadway pollution	NO_2	USA (California)
		Oudin *et al.* [183]	NO_2, O_3, PM_{10}	PM_{10} (during warm season)	Sweden (Gothenburg)
		Shin *et al.* [54]	CO, NO_2, PM_{10}, SO_2	CO, NO_2, PM_{10}	South Korea
		Wang *et al.* [55]	$PM_{2.5}$	$PM_{2.5}$	China (158 prefectures)
	Self-harm and suicide	Biermann *et al.* [68]	O_3	O_3	Germany (Middle Franconia, Bavaria)
		Kim *et al.* [69]	$PM_{2.5}$, PM_{10}	$PM_{2.5}$, PM_{10}	South Korea (Seoul; Busan; Incheon; Daejeon; Daegu; Gwangju; Ulsan)

Table 1 (*Continued*)

Category	Outcome	Author(s), year	Pollutants measured	Pollutants with significant effects	Location
		Szyszkowicz *et al.* [72]	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.* [73]	CO, NO_x, O_3, PM_{10}, SO_2	CO, O_3, PM_{10}, SO_2	Taipei City
		Bakian *et al.* [74]	NO_2, $PM_{2.5}$, PM_{10}, SO_2	NO_2, $PM_{2.5}$	USA (Salt Lake County, Utah)
		Kim *et al.* [75]	CO, NO_2, O_3, PM_{10}, SO_2	O_3, PM_{10}	South Korea (16 administrative regions)
		Lin *et al.* [76]	NO_2, PM_{10}, SO_2	NO_2, PM_{10}, SO_2 (cool seasons only)	China (Guangzhou, Guangdong Province)
		Ng *et al.* [77]	NO_2, $PM_{2.5}$, SO_2, SPM	NO_2, $PM_{2.5}$, SO_2	Japan (Tokyo)
		Casas *et al.* [78]	O_3, PM_{10}	O_3, PM_{10}	Belgium
		Liu *et al.* [67]	CO, NO_2, O_3, $PM_{2.5}$, SO_2	CO, O_3, $PM_{2.5}$	China (Jiangsu Province)
		Kim *et al.* [79]	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*. [70]	CO, NO_2, O_3, PM_{10}, SO_2	CO, NO_2, PM_{10}, SO_2	South Korea (26 cities)
		Min *et al.* [71]	NO_2, PM_{10}, SO_2	NO_2, PM_{10}, SO_2	South Korea
		Szyszkowicz *et al*. [66]	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.* [80]	PAHs	PAHs	USA (New York City, New York)
		Perera *et al.* [81]	PAHs	PAHs	USA (New York City, New York)
		Edwards *et al.* [84]	PAHs	PAHs	Poland (Krakow)
		Sanders [85]	TSP	TSP	USA (Texas)
		Vrijheid *et al.* [86]	Gas cooking	Gas cooking	Spain
		Guxens *et al.* [87]	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.* [88]	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.* [89]	PAHs	PAHs	Poland (Krakow)
		Lertxundi *et al.* [90]	NO_2, $PM_{2.5}$, benzene	NO_2, $PM_{2.5}$	Spain (Guipúzcoa)
		Yorifuji *et al.* [91]	NO_2, SPM, SO_2	NO_2, SPM, SO_2	Japan
		Bharadwaj *et al.* [82]	AQI (CO, O_3, PM_{10})	AQI (CO, O_3, PM_{10})	Chile (Santiago)
		Isen *et al.* [83]	TSP	TSP	USA
	Cognitive functioning (children and youths)	Coscia *et al.* [92]	Pb	Pb	USA (Cincinnati, Ohio)
		Braun *et al.* [123]	Pb	Pb	USA
		Pastor *et al.* [100]	Respiratory hazard ratio	Respiratory hazard ratio	USA (Los Angeles, California)
		Suglia *et al.* [102]	Black carbon	Black carbon	USA (Boston, Massachusetts)
		Calderón-Garcidueñas *et al.* [101]	O_3, $PM_{2.5}$, PM_{10}	O_3, $PM_{2.5}$, PM_{10}	Mexico (Mexico City; Polotitlán)
		Tang *et al.* [103]	Hg, PAHs, Pb	PAHs, Pb	China (Chongqing)
		Froehlich *et al.* [124]	Pb	Pb	USA
		Morales *et al.* [104]	NO_2	NO_2	Spain (Menorca)
		Wang *et al.* [105]	NO_2	NO_2	China (Quanzhou, Fujian Province)
		Freire *et al.* [106]	NO_2	n.s.	Spain (Granada)

Table 1 (*Continued*)

Category	Outcome	Author(s), year	Pollutants measured	Pollutants with significant effects	Location
		Mohai *et al.* [107]	EPA's risk-screening environmental indicator	EPA's risk-screening environmental indicator	USA (Michigan)
		Siddique *et al.* [125]	NO_x, PM_{10}, SO_x	PM_{10}	India (Delhi)
		van Kempen *et al.* [93]	NO_2	NO_2	Netherlands (Amsterdam)
		Chiu *et al.* [94]	Black carbon	Black carbon	USA (Boston, Massachusetts)
		Harris *et al.* [88]	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.* [95]	Traffic exposure	Traffic exposure	Belgium (Flanders)
		Stafford [96]	Indoor air quality	Indoor air quality	USA (Texas)
		Sunyer *et al.* [97]	Elemental carbon, NO_2, UFP	Elemental carbon, NO_2, UFP	Spain (Barcelona)
		Ebenstein *et al.* [98•]	$PM_{2.5}$	$PM_{2.5}$	Israel
		Min and Min [129]	NO_2, PM_{10}	NO_2, PM_{10}	South Korea
		Wang *et al.* [99]	$PM_{2.5}$	$PM_{2.5}$	USA (Los Angeles)
	Cognitive functioning (young and old adults)	Sun and Gu [108]	API (CO, NO_2, O_3, PM_{10}, SO_2)	API (CO, NO_2, O_3, PM_{10}, SO_2)	China (171 cities)
		Chen and Schwartz [109]	O_3, PM_{10}	O_3	USA
		Ranft *et al.* [115]	PM_{10}, residential distance to the next busy road	Residential distance to the next busy road	Germany (the Ruhr area)
		Zeng *et al.* [116]	API	API	China (866 counties)
		Power *et al.* [117]	Black carbon	Black carbon	USA (Greater Boston area, Massachusetts)
		Wellenius *et al.* [118]	Residential distance to the nearest major roadway	Residential distance to the nearest major roadway	USA (Boston, Massachusetts)
		Weuve *et al.* [119]	$PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10}	$PM_{2.5}$, $PM_{2.5\text{-}10}$	USA
		Loop *et al.* [184]	$PM_{2.5}$		USA (48 states)
		Ailshire and Crimmins [121]	$PM_{2.5}$	$PM_{2.5}$	USA
		Ailshire and Clarke [120]	$PM_{2.5}$	$PM_{2.5}$	USA
		Gatto *et al.* [122]	NO_2, O_3, $PM_{2.5}$	$PM_{2.5}$	USA (Los Angeles, California)
		Tonne *et al.* [110]	$PM_{2.5}$, PM_{10}	$PM_{2.5}$, PM_{10}	UK (London)
		Schikowski *et al.* [111]	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.* [112]	$PM_{2.5}$	$PM_{2.5}$	USA (50 northeastern cities)
		Oudin *et al.* [126]	NO_x	NO_x	Sweden (Umeå)
		Cacciottolo *et al.* [127]	$PM_{2.5}$	$PM_{2.5}$	USA (48 states)
		Chen *et al.* [128]	NO_2, $PM_{2.5}$	NO_2, $PM_{2.5}$	Canada (Ontario)
		Zhang *et al.* [113••]	API (NO_2, PM_{10}, SO_2)	API (NO_2, PM_{10}, SO_2)	China (162 counties)
		Heyes *et al.* [114]	$PM_{2.5}$	$PM_{2.5}$	Canada (Ottawa)
	Decision making	Archsmith *et al.* [131]	CO, O_3, $PM_{2.5}$	CO, $PM_{2.5}$	USA
		Huang *et al.* [133]	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.* [130]	AQI	AQI	China (105 cities)

Table 1 (*Continued*)

Category	Outcome	Author(s), year	Pollutants measured	Pollutants with significant effects	Location
Psychological (behavioral)	Avoidance behavior	Bresnahan *et al.* [134]	CO, NO_2, O_3, SO_2	O_3	USA (Los Angeles, California)
		Mansfield *et al.* [135]	AQI	AQI	USA (35 metropolitan areas)
		Currie *et al.* [142]	CO, O_3, PM_{10}	CO	USA (Texas)
		Graff Zivin and Neidell [136]	O_3 alert	O_3 alert	USA (Southern California)
		Neidell [140]	O_3 alert	O_3 alert	USA (Southern California)
		Wen *et al.* [137]	AQI alert	AQI alert	USA (Colorado; Florida; Indiana; Kansas; Massachusetts; Wisconsin)
		Moretti and Neidell [138]	O_3	O_3	USA (Los Angeles, California)
		Noonan [141]	O_3 alert	O_3 alert	USA (Atlanta, Georgia)
		Hales *et al.* [143]	$PM_{2.5}$, PM_{10}	$PM_{2.5}$, PM_{10}	USA (Utah)
		Saberian *et al.* [139]	AQI alert	AQI alert	Australia (Sydney)
		Liu and Salvo [144]	$PM_{2.5}$	$PM_{2.5}$	China (a major urban center)
	Defensive expenditure	Sun *et al.* [145]	$PM_{2.5}$	$PM_{2.5}$	China
		Chang *et al.* [148*]	AQI	AQI	China
		Liu *et al.* [147]	$PM_{2.5}$ alert	$PM_{2.5}$ alert	China (Beijing; Tianjin; Shanghai; Guangzhou; Chengdu; Chongqing; Shenyang; Xi'an)
		Zhang and Mu [146]	AQI	AQI	China (190 cities)
	Migration	Kahn [185]	O_3	O_3	USA (California counties)
		Lu *et al.* [149]	Smog risk perception	Smog risk perception	China (Beijing–Tianjin–Hebei region)
		Qin and Zhu [150]	AQI	AQI	China (153 cities)
Economic	Work productivity (absenteeism)	Ostro [151]	Sulfate, TSP	TSP	USA (84 metropolitan statistical areas)
		Hansen and Selte [152]	NO_2, PM_{10}, SO_2,	PM_{10}	Norway (Oslo)
		Hanna and Oliva [153]	SO_2	SO_2	Mexico (Mexico City)
		Aragón *et al.* [154]	NO_2, $PM_{2.5}$, PM_{10}, SO_2	NO_2, $PM_{2.5}$	Peru (Lima)
		Jans *et al.* [155]	PM_{10}	PM_{10}	Sweden
	Work productivity (presenteeism)	Graff Zivin and Neidell [156]	O_3	O_3	USA (Central Valley, California)
		Chang *et al.* [157]	$PM_{2.5}$	$PM_{2.5}$	USA (Northern California)
		Chang *et al.* [158*]	API	API	China (Shanghai; Nantong, Jiangsu Province)
		He *et al.* [159]	$PM_{2.5}$, SO_2	$PM_{2.5}$, SO_2	China (Henan Province; Jiangsu Province)
	Stock markets	Levy and Yagil [160]	AQI	AQI	USA (New York; Philadelphia)
		Levy and Yagil [165]	AQI	AQI	Australia, Canada, China, Netherlands, USA
		Demir and Ersan [164]	PM_{10}	PM_{10}	Turkey (Istanbul; Ankara; Izmir)
		Lepori [163]	PM, NO_x, SO_2	PM, NO_x, SO_2	Italy (Milan)
		Li and Peng [161]	AQI	AQI	China
		He and Liu [162]	AQI	AQI	China (Shanghai)
Social	Crime and unethical behavior	Nevin [166]	Pb	Pb	USA
		Dietrich *et al.* [170]	Pb	Pb	USA (Cincinnati, Ohio)
		Stretesky and Lynch [171]	Pb	Pb	USA (all counties in the contiguous 48 states)
		Gong *et al.* [172]	AQI, perceived pollution	AQI, perceived pollution	China
		Nevin [173]	Pb	Pb	Australia, Canada, Finland, France, West Germany, Italy, New Zealand, UK, USA

Table 1 (*Continued*)

Category	Outcome	Author(s), year	Pollutants measured	Pollutants with significant effects	Location
		Reyes [174]	Pb	Pb	USA (50 states and DC)
		Haynes *et al.* [175]	Hg, Mn, Pb, $PM_{2.5}$, PM_{10}	Hg, Mn, $PM_{2.5}$, PM_{10}	USA (all 88 Ohio counties)
		Reyes [176]	Pb	Pb	USA (50 states and DC)
		Fehr *et al.* [177•]	$PM_{2.5}$, perceived pollution	Perceived pollution	China (Wuhan, Hubei Province)
		Lu *et al.* [38•]	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 (9360 cities)
		Younan *et al.* [167]	$PM_{2.5}$	$PM_{2.5}$	USA (Southern California)
		Burkhardt *et al.* [168]	O_3, $PM_{2.5}$	O_3, $PM_{2.5}$	USA
	Perception of the government	Huang *et al.* [181]	NO, N_2O, PM_{10}, SO_2, dust, smoke, perceived pollution	PM_{10}, dust, smoke, perceived pollution	China (36 cities) and 56 countries
		Shi and Guo [180]	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 10 μm; $PM_{2.5}$, particulate matter with an aerodynamic diameter less than 2.5 μm; SO_2, sulfur dioxide; SPM, suspended particulate matter; TSP, total suspended particulate; UFP, ultrafine particulate matter.

objective measures from hospitals [40–48]. In a series of studies, Szyszkowicz *et al.* 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 [88,92–97,98•,99–107], to young and old adults [108–112,113••,114–122]. The impacted cognitive outcomes include attention, visuo-construction, memory, math ability, reading comprehension, verbal intelligence, and non-verbal intelligence. For example, Ebenstein *et al.* [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 *et al.* [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 *et al.* [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 *et al.* [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 *et al.* [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 *et al.* [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* [156,157,158•,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 *et al.* [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•,166–176,177•]. For example, analyzing a nine-year panel of 9360 U.S. cities, Lu *et al.* [38•] found that air pollution predicted both violent crimes (murder, rape, robbery, assault) and property crimes (burglary, motor vehicle theft). Similarly, Bondy *et al.* [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•,178,179]. Consistent with these findings, Chew *et al.* [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 *et al.* [181] provided experimental evidence for the psychological experience of air pollution on perceived corruption: When individuals recalled hazy (versus cloudy) days, they were more likely to perceive the government as corrupt.

Limitations of past research and future directions

Data versus 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 versus 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 *et al.* [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 statement

None declared.

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- • of special interest
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