Review article

Estimating error in using ambient $PM_{2.5}$ concentrations as proxies for personal exposures: A Review

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Running head**:** Ambient and personal $PM_{2.5}$ meta-analysis

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ABSTRACT

Background: Several methods have been used to account for measurement error inherent in using the ambient concentration of particulate matter < 2.5 µm ($PM_{2.5}$, ug/m^3) as a proxy for personal exposure. Common features of such methods are their reliance on the estimated correlation between ambient and personal $PM_{2.5}$ concentrations (r). However, extant studies of r have not been systematically and quantitatively assessed for publication bias or heterogeneity. Methods: We searched seven electronic reference databases for studies of the within-participant, ambient-personal $PM_{2.5}$ correlation. Results: The search identified 567 candidate studies, eighteen (3%) of which met inclusion criteria and were abstracted by two co-authors. The studies were published between 1999 and 2008. They represented 619 non-smoking participants aged 6-93 years in seventeen European and North American cities among whom r (Pearson 37%; median 0.54; range 0.09, 0.83) was estimated based on a median of eight ambient-personal $PM_{2.5}$ pairs per participant (range 5, 20) collected over 27 to 547 days. Overall, there was little evidence for publication bias (funnel plot symmetry tests: Begg's log rank test P=0.9; Egger's regression asymmetry test P=0.2); however strong evidence for heterogeneity was noted ($P_{\text{Cochran}} < 0.001$). Of the twenty characteristics examined, European locales, eastern longitudes in North America, higher ambient $PM_{2.5}$ concentrations, higher relative humidity, and lower between-participant variation in r were associated with increased r. Conclusions: Collectively, these findings suggest that characteristics of participants, studies and the environments in which they are conducted may affect the accuracy of ambient $PM_{2.5}$ as a proxy for personal exposure.

Key words: $PM_{2.5}$, meta-analysis, air pollution, measurement error

Abbreviations: CI, confidence interval; PM, particulate matter; $PM_{2.5,}$ particulate matter < 2.5 ug/m^3; $PM_{10,}$ particulate matter <10 ug/m^3; *r,* within-participant ambient-personal $PM_{2.5}$ correlation; SLP, sea level pressure

Several studies have examined methods of accounting for the effects of error associated with using ambient particulate matter (PM) concentrations as proxies for personal PM exposures.[1-3] The National Morbidity and Mortality and Air Pollution Study investigators, for example, compared two such methods: regression calibration and multi-stage Poisson regression.[4] Although such strategies are potentially useful, the comparison relied on only five estimates of the cross-sectional association between personal and ambient PM_{10} concentrations in a convenience sample of panel studies representing 292 participants from four geographic locations. The use of a five-study convenience sample deserves reconsideration, as non-random study selection may provide biased inferences.[5] Another important limitation is that cross-sectional PM correlations may be weaker than longitudinal, within-person PM correlations due to inter-individual variation in behaviors influencing exposure.[6-8]

Moreover, extant studies of the ambient-personal $PM_{2.5}$ correlation and, perhaps more importantly, studies of the modifying effects of participant, study and environment characteristics on this correlation have not been systematically and quantitatively reviewed. Summary estimates of the correlation, which could otherwise be exploited in adjustments for error inherent in using ambient $PM_{2.5}$ concentrations as proxies for personal PM exposures, are therefore unavailable. To address this gap, we systematically and quantitatively reviewed the literature estimating within-participant, ambient-personal $PM_{2.5}$ correlations and determined the extent and sources of measurement error inherent in using ambient $PM_{2.5}$ as a surrogate for personal exposure. These results will facilitate quantification of bias resulting from the use of ambient $PM_{2.5}$ as a proxy for personal exposure in a Women's Health Initiative (WHI) ancillary study, the Environmental Epidemiology of Arrhythmogenesis in the WHI.

MATERIALS AND METHODS

Systematic Review Strategy

A search strategy was devised to identify studies of the within-participant, ambient-personal or outdoor-personal $PM_{2.5}$ correlation. No document type, language, or publication starting-date limitations were used. Searches were conducted in PubMed (1950 to date), ISI Web of Science (1955 to date), ISI BIOSIS Previews (1969 to date), CSA Environmental Sciences and Pollution Management (1967 to date), Toxline (1965 to date), and Proquest Dissertations & Theses (1861 to date) on November 12, 2007. STN EMBASE (1974 to date) was searched on December 14, 2007.

The following strategy was used to search PubMed: (PM 2.5 OR PM2.5 OR PM25 OR PM 25 OR fine particle*) AND (ambient OR outdoor OR outdoors OR outside OR exterior OR external OR background OR fixed site*) AND (individual OR personal) AND (correlat* OR associat* OR relat* OR compar* OR pearson OR spearman). The same four sets of keywords were adapted for input into Web of Science, BIOSIS, Environmental Sciences, Toxline, and EMBASE. The Dissertations & Theses search only required the first three sets of keywords to create a small enough result set for review.

Citations were downloaded to an electronic reference manager (EndNote X1®, Thomson Reuters), de-duplicated, and supplemented with secondary references. The citations were independently reviewed (CLA, KTM) with respect to three inclusion criteria: measurement of ambient $PM_{2.5}$, measurement of personal $PM_{2.5}$, and estimation of the within-participant, ambient-personal $PM_{2.5}$ correlation. Study, participant and environment characteristics were extracted (CLA, KTM) from all articles meeting inclusion criteria. Study characteristics included journal of publication, publication date, setting, study dates, sample size, duration, timing (consecutive; non-consecutive), lower limit of $PM_{2.5}$ detection, number (minimum; mean) of paired $PM_{2.5}$ measures, and correlation metric (Pearson; Spearman). Participant characteristics included age (mean; minimum; maximum), % female, and the presence of comorbidities (pulmonary; cardiovascular; multiple; neither). Environmental characteristics included the mean, median and standard deviation of $PM_{2.5}$ concentrations (ambient; personal), the within-participant, ambient-personal $PM_{2.5}$ correlation coefficients and corresponding number of paired measurements, season, distance to monitor, monitor type, air exchange rate, % of time using air conditioning, and % of time with windows open. Discrepant exclusions and extractions were adjudicated by consensus. Supplemental data were requested from authors by electronic mail as needed. City-specific longitudes and latitudes were obtained from the GEOnet Names Server (GNS, http://earth-info.nga.mil/gns/html/whatsnew.htm#C3). Meteorological data were obtained from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climateresearch.html).

Statistical analysis

Uniform measures of association for the j^{th} study were estimated from the personal-ambient $PM_{2.5}$ correlations measured within each of the i^{th} participants. Each within-participant correlation coefficient (r_i) was converted to its variance-stabilizing, Fisher's z-transform (Z_{r_i}) = $\frac{1}{2}\log_e\left(\frac{1+r_i}{1-r_i}\right)$ [9]. Estimates of the within-participant variance (v_i) = $\frac{1}{n_i - 3}$ and between-participant variance (τ_j^2) = $\frac{Q_j - (k_j - 1)}{c}$ for the j^{th} study were estimated from the number of paired personal-ambient $PM_{2.5}$ measurements for each participant (n_i), the number of participants per study (k_j), the weighted sum of squared errors (Q_j) = $\sum_{i=1}^{k}(n_i - 3)(Z_{r_i} - \overline{Z}_{r_i})^2$, and a constant ($c$)

$$= \sum_{i=1}^{k}(n_i - 3) - \frac{\sum_{i=1}^{k}(n_i - 3)^2}{\sum_{i=1}^{k}(n_i - 3)}$$. The transformed effect size for the j^{th} study is given by

$\overline{Z}_j = \frac{\sum_{i=1}^{k} w_i Z_{ri}}{\sum_{i=1}^{k} w_i}$ with weights (w_i) = $\left(\frac{1}{n_i - 3} + \tau_j^2\right)^{-1}$ and standard error (s_j) = $\sqrt{\frac{1}{\sum_{i=1}^{k} w_i}}$ [10]. Negative τ^2 estimates were set to 0. Fixed-effects summary estimates were approximated using the median correlation coefficient and the average number of paired measurements for two studies [11,12] that did not provide participant-specific correlation coefficients.

Funnel plot asymmetry was assessed using a plot of W_j versus $\overline{Z}_j$, the adjusted rank correlation and regression asymmetry tests [13,14], and a non-parametric "trim and fill" method that imputes hypothetically missing results due to publication bias [15]. In the absence of publication bias, plots of W_j versus $\overline{Z}_j$ usually resemble a symmetrical funnel with the more precise estimates forming the spout and the less precise estimates forming the cone, while low P values associated with the former tests (P_{Begg}; P_{Egger}) give evidence of asymmetry.

Inter-study heterogeneity was evaluated using a plot of $\frac{\overline{Z}_j}{s_j}$ versus $\frac{1}{s_j}$ [16] and Cochran's Q test [17]. The plot and test are related in that the position of the j^{th} study along the vertical axis illustrates its contribution to Q test statistic. In the absence of heterogeneity, all studies fall within the 95% confidence limits and $P_{Cochran} > 0.1$.

Variation in the strength and precision of $\overline{Z}_j$ across levels of the study, environment, and participant characteristics was first assessed by estimating a summary random-effects estimate of $\overline{Z}$ within each study, environment and participant category [18]. A series of univariable random-effects meta-regression models were also constructed to relate each study, environment, and participant characteristic to differences in $\overline{Z}$. Lastly, a multivariable random-effects meta-regression model and a backwards elimination strategy were used to evaluate ten study, participant, and environment characteristics routinely available in epidemiologic studies of $PM_{2.5}$ health effects: latitude, longitude, presence of comorbidities, mean age, % female, mean ambient $PM_{2.5}$, relative humidity, sea level pressure (SLP), and mean temperature. Interval-scale characteristics were analyzed before and after dichotomization at their medians unless noted otherwise. All analyses were performed using STATA (College Station, TX). To facilitate interpretation, estimates of $\overline{Z}$ were back-transformed to their original metric $\bar{r}$ after data analysis.

RESULTS

Our systematic review identified 567 candidate studies for screening. Of these studies, eighteen (3%) met criteria for critical appraisal and were abstracted. Abstracted studies were published between 1999 and 2008 (Table 1). The studies they described were set in seventeen North American and European cities, ten states or provinces and four countries, although 68% were performed in the U.S. (Figure 1). The studies were conducted between 1995 and 2002. The mean study duration was 2.0 months (range 0.9, 18.2), a period in which 79% of the studies collected $PM_{2.5}$ data over consecutive days. During data collection, the studies recorded an average of eight (range 5, 20) ambient and personal $PM_{2.5}$ concentration pairs per participant on which their Pearson (37%) and Spearman (63%) correlation coefficients were based (Table 1).

The studies represented 619 non-smoking participants aged 6-93 (median = 70) years, 60% of whom were female and 41% of whom did not report chronic pulmonary or cardiovascular disease (Table 2). Ambient $PM_{2.5}$ concentrations (range 8.3, 25.2 ug/m^3) were lower than personal $PM_{2.5}$ concentrations (range 9.3, 28.6 ug/m^3) overall, with a median personal-ambient $PM_{2.5}$ difference of 0 (range -9.0, 16.3) (Table 3). The estimated $\bar{r}$ (median 0.54; range 0.09, 0.83) and its standard deviation (median 0.12; range 0.04, 0.31) varied widely (Table 3, Figure 2), the latter reflecting variability in sample weights (median 82.7; range 10.3, 552.0). Estimates of r_i were similarly variable among studies (median interquartile range (IQR) 0.38; range 0.22, 1.04), as were temperature (range -6.0, 24.6 °C) and relative humidity (range 43.9, 87.4%), especially when comparing medians from single-season studies (44%).

Figure 3, a funnel plot of z, suggests little evidence of asymmetry. This was consistent with $P_{Begg} = 0.9$ and $P_{Egger} = 0.2$, but the "trim and fill" method imputed four hypothetically missing studies with $r < 0.15$. Figure 4, a Galbraith plot in which twelve correlation coefficients (44%) fell outside the 95% confidence bounds, provided strong evidence of heterogeneity. This evidence was consistent with $P_{Cochran} < 0.001$.

The interquartile range (IQR) of r_i (≥ 0.41 versus < 0.41) was the study, participant or environment characteristic associated with the greatest difference in $\bar{r}$ (95% CI) = -0.37 (-0.53, -0.20) (Figure 5). Studies conducted in Europe, with eastern longitudes in North America, higher mean ambient $PM_{2.5}$ concentrations, and higher relative humidity were also associated with moderate increases in the within-participant ambient-personal $PM_{2.5}$ correlation coefficient, although imprecision was noted. After restricting to North American studies given the considerable heterogeneity by study locale and small number of European studies (n = 2), higher mean ambient $PM_{2.5}$ concentrations and higher relative humidity were the only characteristics associated with an increased $\bar{r}$ ($P < 0.05$).

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DISCUSSION

Human activity pattern surveys suggest that people spend more than 85% of their time indoors,[19] where they are exposed to numerous sources of indoor $PM_{2.5}$, the physico-chemical properties and toxicities of which often differ from those of ambient $PM_{2.5}$.[20,21] Thus, estimates of personal $PM_{2.5}$ exposure based on ambient concentrations are associated with some degree of uncertainty, prompting the suggestion that epidemiologic studies should only use ambient PM as a surrogate for outdoor, not total, PM exposure.[22-26] Despite these suggestions, certain studies are often cited to justify using ambient $PM_{2.5}$ concentrations as proxies for total personal $PM_{2.5}$ exposures.[8,27-29] These studies report strong within-participant ambient-personal $PM_{2.5}$ correlations exceeding 0.60. Other studies, which report ambient-personal $PM_{2.5}$ correlations below 0.10[30] are rarely cited.

Motivated by this apparent pattern of citations, we reviewed studies of the within-participant ambient-personal $PM_{2.5}$ correlation and examined them for publication bias and heterogeneity. We found low potential for publication bias, although the "trim and fill" analysis imputed four hypothetically missing studies. These hypothetically missing studies most likely represent unpublished findings because they differed considerably from the majority of the published literature, could not be used to justify reliance on ambient $PM_{2.5}$ as a proxy for personal $PM_{2.5}$ exposure, or were considered implausible. Although an alternative explanation is that they represent studies this meta-analysis did not identify, this is less likely since we extensively reviewed seven electronic reference databases, evaluated secondary sources, and did not apply any document type, language, or publication starting-date limitations. Indeed, this systematic review possessed all the distinguishing features of a meta-analysis deemed necessary to ensure its sensitivity.[31-33]

Although there was little evidence for pronounced publication bias, we found strong evidence for heterogeneity in $\bar{r}$ —evidence that contraindicated estimation of a single summary measure to represent the entire literature. The direct associations between European locales, eastern longitudes in North America and increased $\bar{r}$ may reflect several regional factors including higher urban $PM_{2.5}$ concentrations[34] or closer proximities to regulatory monitors. Furthermore, the direct associations between ambient $PM_{2.5}$ concentrations, relative humidity and $\bar{r}$ may reflect increased contribution of ambient $PM_{2.5}$ to personal exposures through activity patterns or air exchange. Although regional differences in geographic, household, and personal factors may explain the indirect association between variation in r_i and $\bar{r}$, further investigation was limited because these factors were uncommon, uncollected, or inconsistently reported. We similarly were unable to determine whether small personal and ambient $PM_{2.5}$ concentration ranges were associated with $\bar{r}$, as few studies reported participant-specific concentrations.

We did not find a strong association between temperature and *r*, but the investigation included several multi-season studies. On the other hand, the scope of this investigation was limited by excluding twelve studies of the cross-sectional ambient-personal $PM_{2.5}$ correlation. Cross-sectional correlations are thought to be weaker than longitudinal, within-person correlations due to inter-individual variation in activities affecting exposure (e.g. spending time near smokers, cooking or cleaning).[6-8] A series of studies conducted in the Netherlands also found that ambient-personal PM correlations were stronger when analyses were conducted longitudinally.[35] Since studies of within- versus between-participant correlations address systematically different questions—the recognition of which precludes simultaneous evaluation[36] —a priori exclusion of cross-sectional correlations was appropriate.

We were unable to determine whether associations based on summary data were good proxies for associations estimated using individual participant data.[37] One method to assess the validity of our conclusions and eliminate the potential for ecologic bias[38] would have been to evaluate individual participant data. A meta-analysis based on individual participant data also would allow for increased flexibility in analyses of heterogeneity and greater consistency of reporting.[39] Although such data were unavailable, the findings reported here were based on a large number of studies and were interpreted cautiously.

The present meta-analysis focused on $PM_{2.5}$ although several European countries also regulate PM_{10}. It remains unclear whether findings for $PM_{2.5}$ extend to PM_{10}, but an ongoing meta-analysis of the personal-ambient PM_{10} correlation will be helpful in evaluating consistency of findings across PM metrics. The current meta-analysis also did not evaluate the association between ambient and personal concentrations of sulfate or elemental carbon, although these combustion products may better represent the influence of outdoor particles because their indoor sources are uncommon.[40-42] Nonetheless, the results presented herein have potentially important implications for studies examining the health effects of $PM_{2.5}$ because methods for modifying regression equations to account for normally distributed measurement error are well established. Although the uniformity with which these results can be applied across study designs deserves additional consideration,[3,6-8,43] Crooks et al. (2008) recently described a Bayesian method for incorporating log-normal measurement error in a cross-sectional study of PM health effects.[44] Log-normal distributions are believed more appropriate for PM, but the application of these methods require knowledge of the conditional distribution of personal exposure given ambient exposure, specifically the mean and standard deviation of the personal exposure distribution, as well as the ambient-personal $PM_{2.5}$ correlations described herein.

Limitations notwithstanding, the present report reinforces the view that characteristics of participants, studies and the environments in which they are conducted affect the accuracy of ambient $PM_{2.5}$ as a proxy for personal exposure. The wide range in estimated correlations between personal and ambient $PM_{2.5}$ and the associations with participant, study, and environment characteristics suggest that the potential for exposure misclassification varies and may be substantial. Thus, these factors warrant greater scrutiny in future studies utilizing ambient $PM_{2.5}$ as a proxy for personal exposure.

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TABLE 1. Characteristics of eighteen studies examining the within-participant, ambient-personal $PM_{2.5}$ correlation.

		Setting			Study Dates			Ambient & Personal $PM_{2.5}$ Measures		
Study	Sub-study	City	State/Province	Country	Start	End	Duration (months)	Timing	Pairs	*r*
Janssen et al. 1999[8]		Wageningen		Netherlands	03/29/1995	06/15/1995	2.5	N	6	P
Ebelt et al. 2000[45]		Vancouver	British Columbia	Canada	04/21/1998	09/25/1998	5.1	N	7	S
Janssen et al. 2000[27]	1	Amsterdam		Netherlands	11/02/1998	06/18/1999	7.4	N	9	S
	2	Helsinki		Finland	11/01/1998	04/30/1999	5.8	N	7	S
Sarnat et al. 2000[28]	1	Baltimore	Maryland	United States	06/29/1998	08/07/1998	1.3	C	9	S
	2				02/02/1999	03/13/1999	1.3	C	9	S
Williams et al. 2000[46]		Towson	Maryland	United States	07/26/1998	08/23/1998	0.9	C	16	P
Rodes et al. 2001[47,48]		Fresno	California	United States	02/01/1999	02/28/1999	0.9	C	6	P
Sarnat et al. 2001[29]	1	Baltimore	Maryland	United States	06/29/1998	08/23/1998	1.8	C	8	S
	2				02/02/1999	03/13/1999	1.3	C	12	
Suh et al. 2003[49]	1	Los Angeles	California	United States	06/12/2000	07/24/2000	1.4	C	NR	NR
	2				02/11/2000	03/22/2000	1.3	C		
Adgate et al. 2003[30]		Minneapolis	Minnesota	United States	04/26/1999	11/21/1999	6.7	C	8	P
Liu et al. 2003[50]	1	Seattle	Washington	United States	10/26/1999	08/10/2000	9.3	C	7	P
	2				10/26/1999	10/26/2000	11.8	C	7	P
	3				02/07/2000	05/24/2001	15.2	C	7	P
	4				11/27/2000	02/24/2001	2.9	C	7	P
Williams et al. 2003[51]		Raleigh	North Carolina	United States	06/09/2000	05/21/2001	11.2	C	20	P
Reid 2003[12]	1	Atlanta	Georgia	United States	09/21/1999	11/23/1999	2.0	C	6	S
	2				04/01/2000	05/13/2000	1.4	C	6	S
Sarnat et al. 2005[41]	1	Boston	Massachusetts	United States	06/13/1999	07/23/1999	1.3	C	12	S
	2				02/01/2000	03/12/2000	1.3	C	12	S
Kim et al. 2006[11]		Toronto	Ontario	Canada	05/02/2000	10/31/2001	17.6	N	9	S
Noullett et al. 2006[52]		Prince George	British Columbia	Canada	02/05/2001	03/16/2001	1.3	N	9	S
Sarnat et al. 2006[42]	1	Steubenville	Ohio	United States	06/04/2000	8/18/2000	2.4	C	17	S
	2				09/24/2000	12/15/2000	2.6	C	20	S
Wu et al. 2006[53]		Pullman	Washington	United States	09/03/2002	11/01/2002	1.9	C	5	P
Brown et al. 2008[40]	1	Boston	Massachusetts	United States	11/15/1999	01/29/2000	2.4	C	6	S
	2				06/06/2000	07/25/2000	1.6	C	6	S
18 studies, 1999 – 2008*	**29**	**17**	**10**	**4**	**1995 – 2002**		**2.0**	**79% C**	**8**	**37% P**

*Summary statistics reported as counts, range, proportion, or median. C= consecutive. N = non-consecutive. Pairs = average number of ambient-personal paired measurements for estimation of within-participant correlations. NR= not reported. P = Pearson product-moment correlation coefficient. $PM_{2.5}$ = particulate matter < 2.5 μm in diameter (μg/m3). *r* = within-participant ambient-personal $PM_{2.5}$ correlation estimation method. S = Spearman's rank correlation coefficient.

TABLE 2. Characteristics of participants in eighteen studies examining the within-participant, ambient-personal $PM_{2.5}$ correlation.

Study	Sub-study	N	Participant Age: Mean	Min	Max	Percent Female	Comorbidity[‡]
Janssen et al. 1999[8]		13	10.8	10	12	54	N
Ebelt et al. 2000[45]		16	74	54	86	56	P
Janssen et al. 2000[27]	1	36	72	55	84	35	C
	2	46	68	54	89	49	C
Sarnat et al. 2000[28]	1	14	75	64	*	60	N
	2	14	75	64	*	60	N
Williams et al. 2000[46]		19	81	72	93	81	N, C, P
Rodes et al. 2001[47,48]		5	85	55	*	68	N
Sarnat et al. 2001[29]	1	6[#]	11	9	13	33	N
	2	28[#]	Children and elderly			†	N, P
Suh et al. 2003[49]	1	15	68.1	55	84	87	P
	2	15	70	60	84	93	P
Adgate et al. 2003[30]		28	42	24	64	72	N
Liu et al. 2003[50]	1	34	76.3	66	88	61	N
	2	51	77.3	65	89	55	P
	3	33	76.6	57	86	35	C
	4	21	9	6	13	24	P
Williams et al. 2003[51]		36	70	55	85	74	C
Reid 2003[12]	1	16	64	33	88	33	C, P
	2	21	63	33	84	50	C, P
Sarnat et al. 2005[41]	1	29	Children and elderly			73	N
	2	27	Children and elderly			83	N
Kim et al. 2006[11]		28	64	49	80	11	C
Noullett et al. 2006[52]		14	11	10	12	53	N
Sarnat et al. 2006[42]	1	10	72.4	*	*	80	N
	2	10	69.8	*	*	90	N
Wu et al. 2006[53]		11	27	18	52	66	P
Brown et al. 2008[40]	1	12	†	40	†	20	C, P
	2	11	†	40	†	27	C, P
18 studies, 1999 - 2008[¥]	**29**	**619**	**70**	**6**	**93**	**60%**	**41% N**

*Not reported; †Not collected; ‡No (N), chronic pulmonary (P), or chronic cardiovascular (C) disease; ¥Summary statistics reported as counts, range, proportion, or median; #Excludes participants in Sarnat et al., 2000[28]

TABLE 3. Characteristics of the environment in eighteen studies examining the within-participant, ambient-personal $PM_{2.5}$ correlation.

		Ambient $PM_{2.5}$ ($\mu g/m^3$)		Personal $PM_{2.5}$ ($\mu g/m^3$)			r		Meteorological data, mean over study dates		
Study,	**Sub-study**	**Mean**	**SD**	**Mean**	**SD**	$\bar{r}$	***SD***	**IQR**	**T (°C)**	**SLP (kPa)**	**RH (%)**
Janssen et al. 1999[8]		17.1	2.8	28.3	11.3	0.83	0.20	0.29	10.6	101.66	76.6
Ebelt et al. 2000[45]		11.4	4.1	18.2	14.6	0.52	0.17	0.70	16.6	101.60	76.6
Janssen et al. 2000[27]	1	20.8	4.0	22.2	25.7	0.72	0.09	0.38	7.8	101.52	84.7
	2	12.7	2.0	10.9	4.4	0.72	0.08	0.26	-1.8	101.10	87.4
Sarnat et al. 2000[28]	1	25.2	11.5	22.3	10.1	0.74	0.12	0.30	24.6	101.56	64.6
	2	20.5	9.4	15.0	14.6	0.40	0.14	0.73	3.1	101.75	59.9
Williams et al. 2000[46]		22.0	12.9	13.0	3.2	0.73	0.07	0.22	24.0	101.85	68.3
Rodes et al. 2001[47,48]	1	22.9	10.1	13.1	5.9	0.44	0.28	0.32	9.6	102.27	75.2
Sarnat et al. 2001[29]	1	24.7	14.0	21.1	8.1	0.60	0.22	0.37	24.4	101.63	66.2
	2	20.1	9.4	18.5	17.8	0.27	0.08	0.41	3.1	101.75	59.9
Suh et al. 2003[49]	1	*	*	25.1	20.8	*	*	*	21.1	101.34	71.3
	2	*	*	19.6	14.5	*	*	*	13.7	101.70	69.7
Adgate et al. 2003[30]		10.1	6.2	26.4	30.2	0.09	0.09	0.57	16.9	101.50	62.7
Liu et al. 2003[50]	1	8.3	5.7	9.3	8.4	0.47	0.11	0.66	9.9	101.78	78.9
	2	8.4	5.7	10.5	7.2	0.40	0.10	0.61	10.8	101.78	77.8
	3	11.9	5.7	10.8	8.4	0.61	0.14	0.60	10.0	101.82	76.0
	4	11.4	5.7	13.3	8.2	0.51	0.11	0.42	6.9	101.90	77.1
Williams et al. 2003[51]		19.2	8.6	23.0	16.1	0.34	0.04	0.29	17.2	101.92	67.4
Reid 2003[12]	1	20.6	9.7	16.3	8.4	0.54	0.14	*	15.7	102.01	68.3
	2	15.7	5.4	15.0	7.5	0.49	0.12	*	17.2	101.64	62.0
Sarnat et al. 2005[41]	1	15.5	12.1	28.6	12.2	0.61	0.07	0.37	22.8	101.58	62.3
	2	11.7	6.8	16.7	9.8	0.35	0.08	0.49	2.6	101.68	60.7
Kim et al. 2006[11]		11.0	8.0	22.0	42.0	0.69	0.27	*	11.0	101.72	73.8
Noullett et al. 2006[52]		18.0	15.0	18.0	13.0	0.54	0.10	0.31	-6.0	102.02	69.4
Sarnat et al. 2006[42]	1	20.1	9.3	19.9	9.4	0.81	0.19	0.35	20.7	101.63	75.0
	2	19.3	12.2	20.1	11.6	0.76	0.11	0.28	7.0	102.12	71.8
Wu et al. 2006[53]		11.5	8.0	13.8	11.1	0.46	0.31	1.04	9.6	101.88	48.1
Brown et al. 2008[40]	1	9.9	5.1	12.0	6.0	0.22	0.26	0.94	2.0	101.67	59.0
	2	11.8	5.5	10.0	6.2	0.68	0.21	0.36	20.4	101.43	70.3
18 studies, 1999 - 2008[†]	**29**	**15.7**	**8.0**	**18.2**	**10.1**	**0.54**	**0.12**	**0.38**	**10.8**	**101.7**	**69.7**

*Data requested, but not provided as of 06/11/09; [†]Summary statistics reported as counts or median. IQR = interquartile range of r between participants within studies. r = within-participant ambient $PM_{2.5}$-personal $PM_{2.5}$ correlation coefficient. RH = relative humidity. SD = standard deviation. SLP = sea level pressure. T = temperature.

Figure 1. Locations of eighteen studies examining the within-participant, ambient-personal $PM_{2.5}$ correlation.

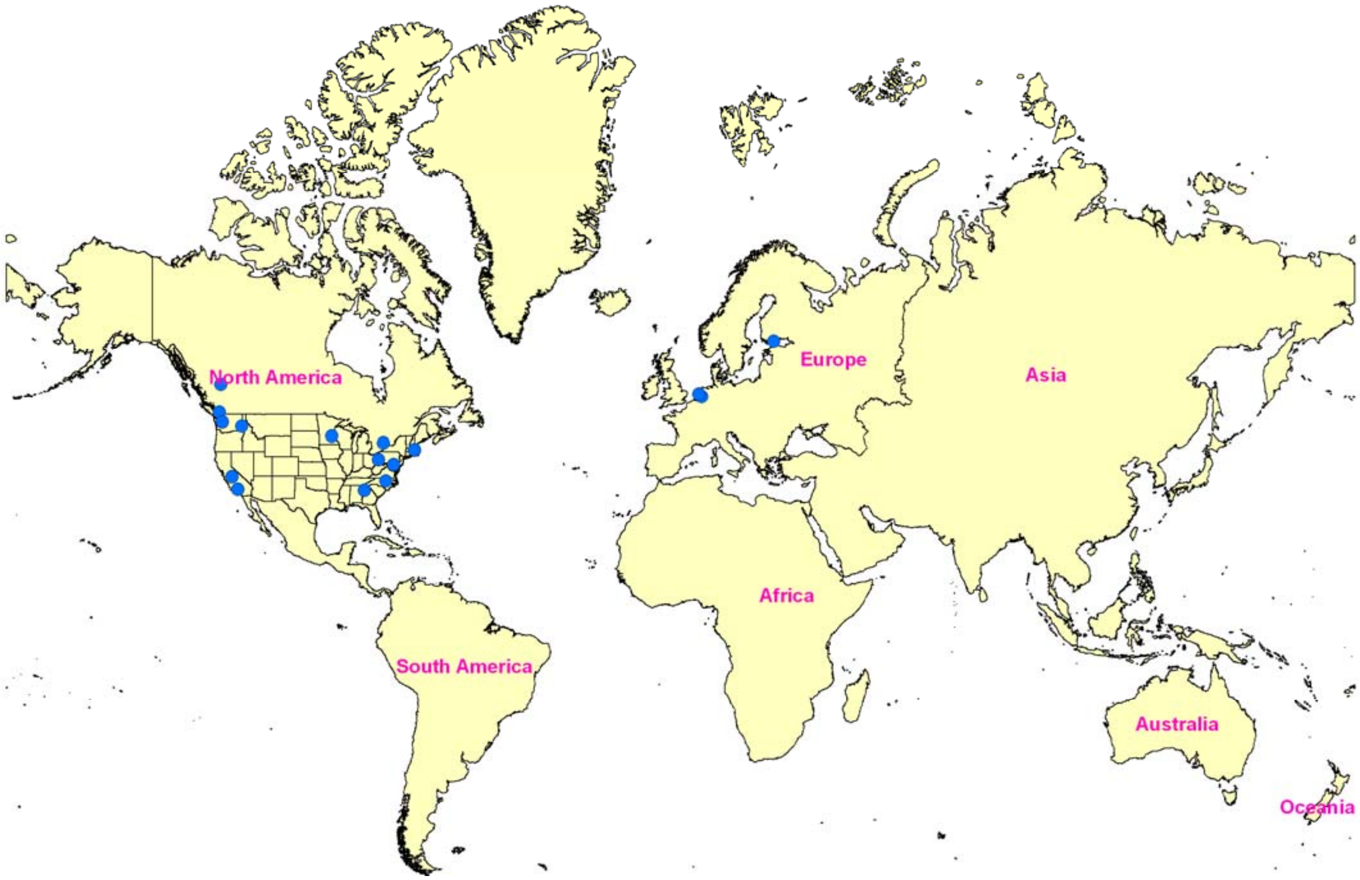


Figure 2. Twenty-seven estimates of $\bar{r}$ (95% CI) from eighteen studies of the within-participant, ambient-personal $PM_{2.5}$ correlation.

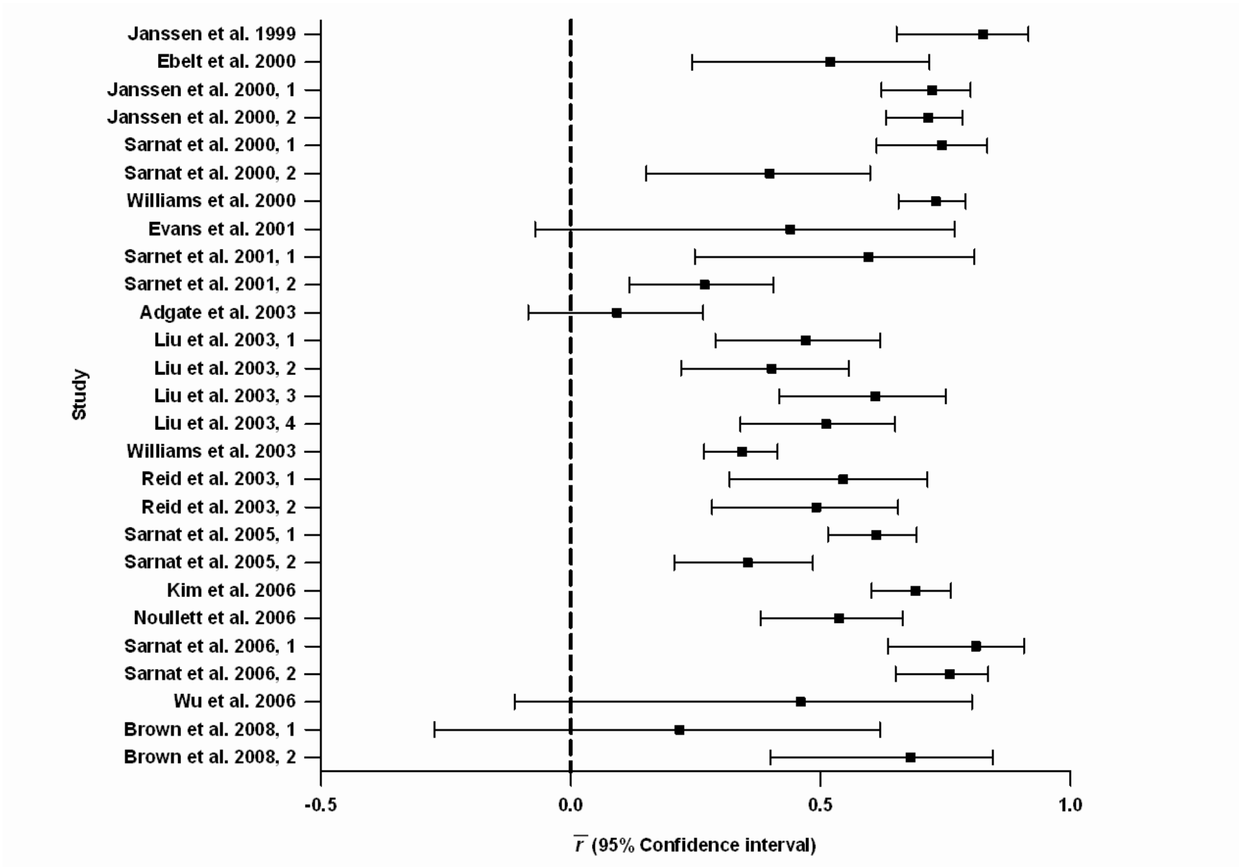


Figure 3. Funnel plot for 27 reported and four imputed estimates of the within-participant, ambient-personal $PM_{2.5}$ correlation.

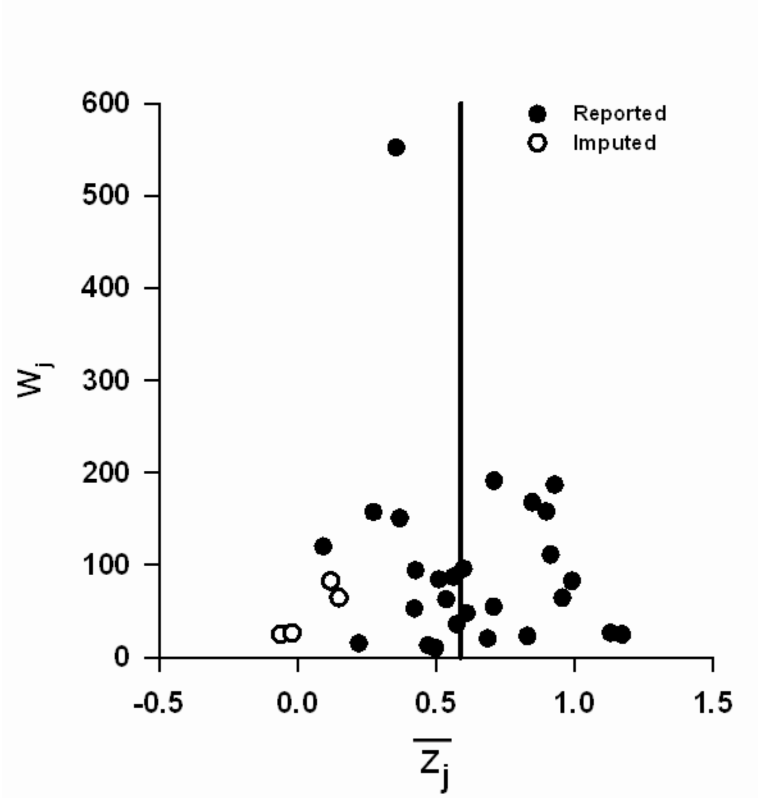


Figure 4. Galbraith plot with 95% confidence limits for 27 estimates of the within-participant, ambient-personal $PM_{2.5}$ correlation.

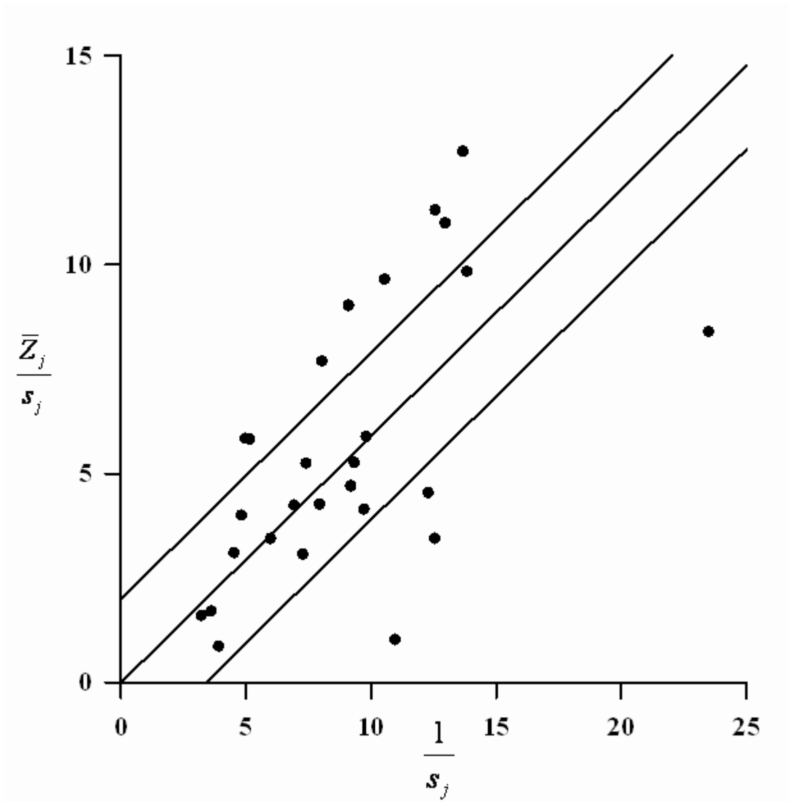
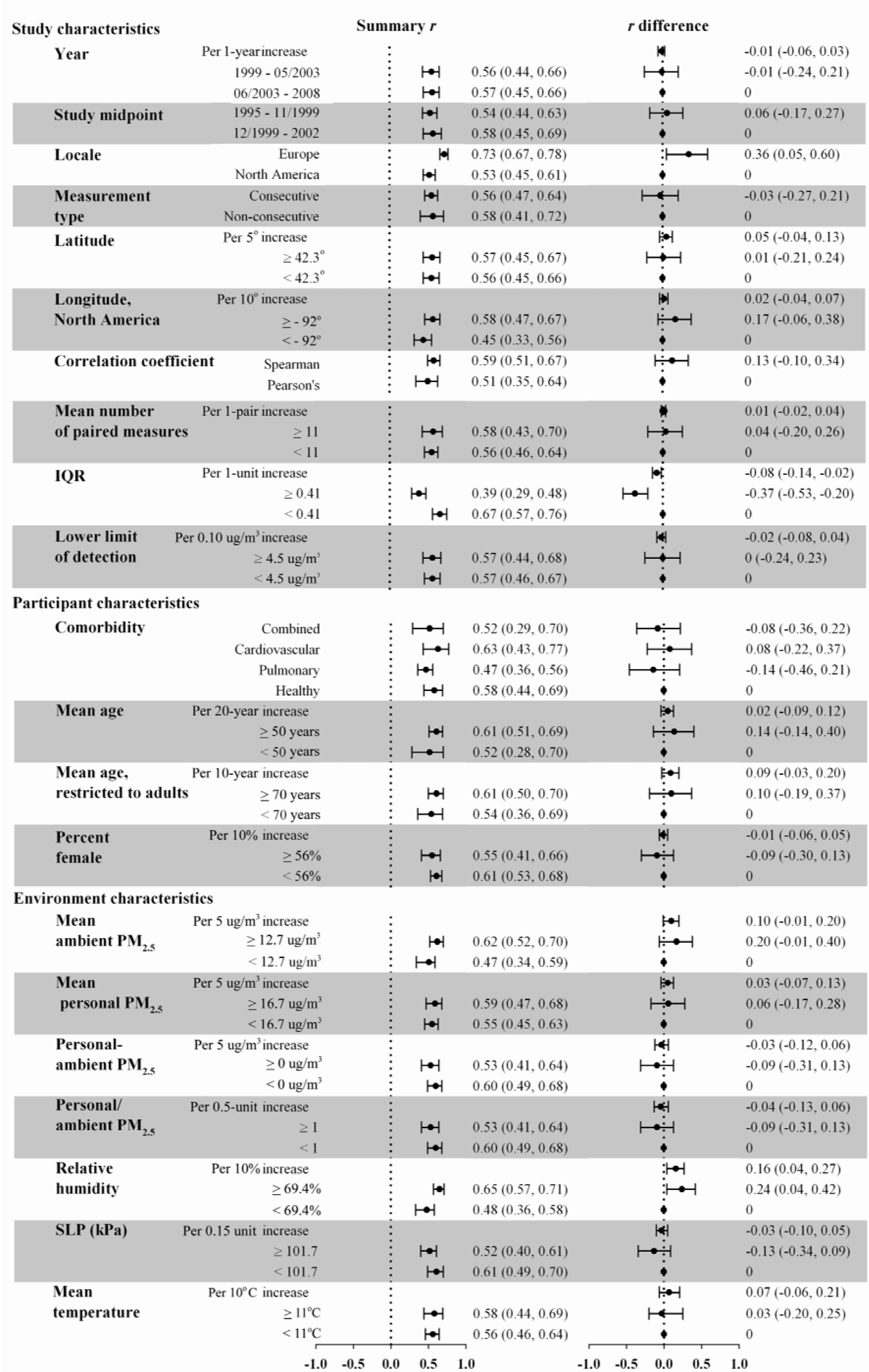


Figure 5. Summary correlations (95% CI) and correlation differences (95% CI) by study, participant, and environment characteristics for eighteen studies examining the within-participant, ambient-personal $PM_{2.5}$ correlation.


Study characteristics
Summary *r*
r difference
Year
Per 1-year increase -0.01 (-0.06, 0.03)
1999 - 05/2003 0.56 (0.44, 0.66) -0.01 (-0.24, 0.21)
06/2003 - 2008 0.57 (0.45, 0.66) 0
Study midpoint
1995 - 11/1999 0.54 (0.44, 0.63) 0.06 (-0.17, 0.27)
12/1999 - 2002 0.58 (0.45, 0.69) 0
Locale
Europe 0.73 (0.67, 0.78) 0.36 (0.05, 0.60)
North America 0.53 (0.45, 0.61) 0
Measurement type
Consecutive 0.56 (0.47, 0.64) -0.03 (-0.27, 0.21)
Non-consecutive 0.58 (0.41, 0.72) 0
Latitude
Per 5° increase 0.05 (-0.04, 0.13)
≥ 42.3° 0.57 (0.45, 0.67) 0.01 (-0.21, 0.24)
< 42.3° 0.56 (0.45, 0.66) 0
Longitude, North America
Per 10° increase 0.02 (-0.04, 0.07)
≥ - 92° 0.58 (0.47, 0.67) 0.17 (-0.06, 0.38)
< - 92° 0.45 (0.33, 0.56) 0
Correlation coefficient
Spearman 0.59 (0.51, 0.67) 0.13 (-0.10, 0.34)
Pearson's 0.51 (0.35, 0.64) 0
Mean number of paired measures
Per 1-pair increase 0.01 (-0.02, 0.04)
≥ 11 0.58 (0.43, 0.70) 0.04 (-0.20, 0.26)
< 11 0.56 (0.46, 0.64) 0
IQR
Per 1-unit increase -0.08 (-0.14, -0.02)
≥ 0.41 0.39 (0.29, 0.48) -0.37 (-0.53, -0.20)
< 0.41 0.67 (0.57, 0.76) 0
Lower limit of detection
Per 0.10 ug/m^3 increase -0.02 (-0.08, 0.04)
≥ 4.5 ug/m^3 0.57 (0.44, 0.68) 0 (-0.24, 0.23)
< 4.5 ug/m^3 0.57 (0.46, 0.67) 0
Participant characteristics
Comorbidity
Combined 0.52 (0.29, 0.70) -0.08 (-0.36, 0.22)
Cardiovascular 0.63 (0.43, 0.77) 0.08 (-0.22, 0.37)
Pulmonary 0.47 (0.36, 0.56) -0.14 (-0.46, 0.21)
Healthy 0.58 (0.44, 0.69) 0
Mean age
Per 20-year increase 0.02 (-0.09, 0.12)
≥ 50 years 0.61 (0.51, 0.69) 0.14 (-0.14, 0.40)
< 50 years 0.52 (0.28, 0.70) 0
Mean age, restricted to adults
Per 10-year increase 0.09 (-0.03, 0.20)
≥ 70 years 0.61 (0.50, 0.70) 0.10 (-0.19, 0.37)
< 70 years 0.54 (0.36, 0.69) 0
Percent female
Per 10% increase -0.01 (-0.06, 0.05)
≥ 56% 0.55 (0.41, 0.66) -0.09 (-0.30, 0.13)
< 56% 0.61 (0.53, 0.68) 0
Environment characteristics
Mean ambient PM$_{2.5}$
Per 5 ug/m^3 increase 0.10 (-0.01, 0.20)
≥ 12.7 ug/m^3 0.62 (0.52, 0.70) 0.20 (-0.01, 0.40)
< 12.7 ug/m^3 0.47 (0.34, 0.59) 0
Mean personal PM$_{2.5}$
Per 5 ug/m^3 increase 0.03 (-0.07, 0.13)
≥ 16.7 ug/m^3 0.59 (0.47, 0.68) 0.06 (-0.17, 0.28)
< 16.7 ug/m^3 0.55 (0.45, 0.63) 0
Personal-ambient PM$_{2.5}$
Per 5 ug/m^3 increase -0.03 (-0.12, 0.06)
≥ 0 ug/m^3 0.53 (0.41, 0.64) -0.09 (-0.31, 0.13)
< 0 ug/m^3 0.60 (0.49, 0.68) 0
Personal/ ambient PM$_{2.5}$
Per 0.5-unit increase -0.04 (-0.13, 0.06)
≥ 1 0.53 (0.41, 0.64) -0.09 (-0.31, 0.13)
< 1 0.60 (0.49, 0.68) 0
Relative humidity
Per 10% increase 0.16 (0.04, 0.27)
≥ 69.4% 0.65 (0.57, 0.71) 0.24 (0.04, 0.42)
< 69.4% 0.48 (0.36, 0.58) 0
SLP (kPa)
Per 0.15 unit increase -0.03 (-0.10, 0.05)
≥ 101.7 0.52 (0.40, 0.61) -0.13 (-0.34, 0.09)
< 101.7 0.61 (0.49, 0.70) 0
Mean temperature
Per 10°C increase 0.07 (-0.06, 0.21)
≥ 11°C 0.58 (0.44, 0.69) 0.03 (-0.20, 0.25)
< 11°C 0.56 (0.46, 0.64) 0
-1.0 -0.5 0.0 0.5 1.0
-1.0 -0.5 0.0 0.5 1.0