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Estimating Volatile Organic Compound Concentrations in Selected Microenvironments Using Time–Activity and Personal Exposure Data

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Repeated measures of personal exposure to 14 volatile organic compounds (VOC) were obtained over 3 seasons for 70 healthy, nonsmoking adults living in Minneapolis–St. Paul. Matched data were also available for participants' time–activity patterns, and measured VOC concentrations outdoors in the community and indoors in residences. A novel modeling approach employing hierarchical Bayesian techniques was used to estimate VOC concentrations (posterior mode) and variability (credible intervals) in five microenvironments: (1) indoors at home; (2) indoors at work/school; (3) indoors in other locations; (4) outdoors in any location; and (5) in transit. Estimated concentrations tended to be highest in "other" indoor microenvironments (e.g., grocery stores, restaurants, shopping malls), intermediate in the indoor work/school and residential microenvironments, and lowest in the outside and in-transit microenvironments. Model estimates for all 14 VOC were reasonable approximations of measured median concentrations in the indoor residential microenvironment. The largest predicted contributor to cumulative (2-day) personal exposure for all 14 VOC was the indoor residential environment. Model-based results suggest that indoors-at-work/school and indoors-at-other-location microenvironments were the second or third largest contributors for all VOC, while the outside-in-any-location and in-transit microenvironments appeared to contribute negligibly to cumulative personal exposure. Results from a mixed-effects model indicate that being in or near a garage increased personal exposure to *o*-xylene, *m/p*-xylene, benzene, ethylbenzene, and toluene, and leaving windows and doors at home open for 6 h or more decreased personal exposure to 13 of 14 VOC, all except trichloroethylene.

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Volatile organic compounds (VOC) are emitted into the air by numerous outdoor sources, such as motor vehicles and industrial processes, and multiple indoor sources, such as personal care products, cleaners, deodorizers, and cigarettes. Consequently, airborne VOC are ubiquitous in both occupational and nonoccupational environments (Spengler & Sexton, 1983; LaGrone, 1991; Samet & Spengler, 1991; Kelly et al., 1994; Woodruff et al., 1998; Morella-Frosch et al., 2000; Wallace, 2001). Human exposures to VOC are a function of air concentrations in Human various microenvironments through which people

move during normal daily activities, and the amount of time they spend in these locations (Sexton & Ryan, 1988; NRC, 1991). Several studies of nonsmokers showed that personal (breathing zone) exposures to an array of VOC were not characterized adequately by outdoor community monitors. This is primarily because people typically spend greater than 90% of their time indoors (e.g., at home or at work), where VOC levels are often higher than matched outdoor concentrations (Wallace et al., 1985, 1988, 1989, 1991; Anderson et al., 2001; Edwards et al., 2001a; Kim et al., 2002; Sexton et al., 2004a, 2004b; Adgate et al., 2004).

The importance of understanding concentrations and time spent in important microenvironments for accurate exposure estimation is well recognized (Spengler & Sexton, 1983; Sexton & Ryan, 1988; NRC, 1991; Schwab et al., 1990; Klepeis et al., 2001; McCurdy & Graham, 2003). In reality, however, it is usually impractical for cost and feasibility reasons to measure VOC concentrations in all or even most of the microenvironments that contribute to an individual's personal exposure. Nearly all studies that assess personal VOC exposure measure concentrations in only two microenvironments: indoors at home—where people tend to spend most of their time—and outdoors in the community—where levels represent a quasi-baseline condition to which indoor sources add their contributions (Wallace et al., 1985, 1988, 1989, 1991; Edwards et al., 2001a, 2001b; Kim et al., 2002; Sexton et al., 2004a, 2004b; Adgate et al., 2004). In this article, the relationship between measured personal exposure to 14 individual VOC and reported time–activity patterns was examined for 70 healthy, nonsmoking adults from Minneapolis–St. Paul. The emphasis was placed on using a novel method to examine the contribution of various microenvironments to measured personal exposure and to estimate airborne concentrations in microenvironments where measurements were not conducted.

METHODS

Study Design

The primary goal of the study was to assess adults' exposure to airborne VOC by measuring personal (breathing zone) concentrations multiple times for each subject and comparing results with concurrent measurements inside participants' residences and outside in their neighborhoods. Three urban neighborhoods in Minneapolis–St. Paul predicted to possess different outdoor VOC concentration profiles were selected for the exposure monitoring study (Pratt et al., 2004). Phillips is an economically disadvantaged, predominantly minority inner-city neighborhood in south-central Minneapolis. Outdoor VOC concentrations in Phillips were predicted to be relatively high because of contributions from multiple sources. East St. Paul is a blue-collar, racially mixed neighborhood in St. Paul, and VOC concentrations were predicted to be relatively high, primarily as a result of emissions from nearby manufacturing plants. Battle Creek is a predominantly White, affluent neighborhood on the eastern edge of St. Paul, and predicted VOC concentrations were relatively low compared to the other two neighborhoods (Pratt et al., 2004).

A centralized outdoor monitoring site was established by the Minnesota Pollution Control Agency (MPCA) in each neighborhood. Seventy-one nonsmoking adults (25 from Battle Creek, 22 from East St. Paul, 24 from Phillips) were recruited using house-to-house canvassing and direct solicitation. Although this was not a probability-based study design, subjects were selected so that participating households were geographically dispersed across each of the three neighborhoods. Baseline questionnaires were used to obtain data on demographic, socioeconomic, and exposure-related variables. Overall, the participants were predominantly White (85%), female (77%), well educated (52% were college graduates), and relatively affluent (38% had annual household income ≥$50,000). Participants maintained time–activity logs during VOC sampling periods, recording the amount of time they spent in seven microenvironments (indoors at home, work/school, other; outdoors at home, work/school, other; in transit), as well as the amount of time they were in close proximity to a smoker.

Two-day samples were collected at the outdoor community sites (O), indoor residential sites (I), and in the personal (P) breathing zone of participants during three monitoring sessions in 1999: spring (April 26–June 20); summer (June 21–August 11); and fall (September 23–November 21). In total, 333 personal exposure samples (including duplicates) with matched time–activity data were obtained from 70 participants. The median number of matched samples collected for each subject was 4, and ranged from a minimum of one (1 person) to a maximum of 11 (1 person). A more detailed description of the study design and results was published previously (Sexton et al., 2004a, 2004b; Pratt et al., 2004, 2005).

Data Collection and Analysis

All O, I, and P VOC concentrations were 2-d average values obtained with 3M model 3500 organic vapor monitors (3500 OVMs), which are charcoal-based passive air samplers. The suitability of these VOC badges for outdoor, indoor, and personal sampling was demonstrated by Chung et al. (1999a, 1999b). These investigators also described the determination of extraction efficiencies and the calculation of method detection limits. Valid and useful analytical results were obtained for 14 VOC (see Table 1). The extraction solvent consisted of a 2:1 v/v mix of acetone and carbon disulfide, which provided a low background for target analytes. All extracts were analyzed by gas chromatography/mass spectrometry (GC/MS) with a Hewlett-Packard 5890 series II Plus GC with an HP 5972 MS detector, HP 18593B autosampler, Vectra 486 computer with EnvironQuant ChemStation Software and NBS75K Spectra Library, using an RTX-1/60 m/0.25 mm ID/1 mm film thickness capillary column. Analytical and internal standards were prepared, and VOC concentrations were calculated as described previously (Chung et al.,

TABLE 1
Summary Statistics (μg/m^3) for VOC Concentrations From Personal Monitors

VOC	n	%Det[b]	Mean	Median	Q10	Q90
Benzene	333	100.0	7.2	3.2	1.4	18.0
Chloroform	333	79.3	1.5	1.0	0.1	3.8
p-Dichlorobenzene	333	83.8	3.1	0.4	0.1	5.0
Ethyl Benzene	333	100.0	5.5	2.1	0.9	11.3
d-Limonene	300[a]	100.0	22.6	11.7	4.1	49.8
Methylene Chloride	333	100.0	6.7	1.4	0.4	13.6
a-Pinene	300[a]	99.7	6.4	2.6	0.9	13.8
b-Pinene	300[a]	76.3	4.1	1.4	0.1	6.7
Styrene	333	85.6	1.0	0.7	0.1	1.9
Tetrachloroethylene	333	99.7	27.8	0.9	0.3	6.4
Toluene	333	99.4	30.4	17.5	5.4	62.9
Trichloroethylene	333	92.5	1.0	0.2	0.0	1.8
o-Xylene	333	100.0	6.5	2.3	1.1	14.4
m/*p*-Xylene	333	100.0	20.3	7.3	3.2	46.4

Note. [a]Fewer valid samples were available because of calibration problems.
[b]Percentage of samples with detectable measurements.

1999a). Duplicate O, I, and P badges were collected periodically during the study (total $n = 80$), and correlation coefficients were >.94 for all individual VOC. The median relative absolute difference (MRAD), which is the median of the ratios of within-pair absolute differences divided by the within-pair mean, was <0.18 for all VOC except trichloroethylene (MRAD = 0.44).

Statistical Issues

Estimation and inference about the concentration of each VOC in each of the seven microenvironments posed some statistical challenges. For each VOC, a single measurement set consists of the 48-h total personal exposure measurement as recorded by the OVM, along with the proportion of the 48 h spent in each of the 7 microenvironments. In this case, a linear model for the expected value of VOC exposure has been suggested (Sexton & Ryan, 1988) as follows:

$$E[V_i] = \sum_{m=1}^{M} C_{(m)} p_{i(m)} \quad (1)$$

with $E[\cdot]$ denoting the expectation operator, and additional definitions as:

V_i : For the ith subject of n overall, the average concentration (μg/m^3) measured by the OVM over the 48-h period.
$C_{(m)}$: The average concentration (μg/m^3) in the mth of M microenvironments.
$P_{i(m)}$: For the ith subject, the proportion of the 48 h spent in the mth microenvironment.

In this study there were repeated measurement sets over time, as well as some duplicate sets, so the model is more complicated, with:

$$E\left[V_{ijk}\right] = \sum_{m=1}^{M} C_{(m)} p_{ij(m)} \quad (2)$$

with V_{ijk} associated with subject i, VMP (VOC monitoring period) j, and replicate k. The time proportion, $P_{ij(m)}$, is not indexed by k because it refers to the same VMP. Repeated measurements from the same subject are correlated. In order to prevent overfitting and bias in favor of those subjects who happen to have contributed the most measurements, the statistical model must account for this within-subject correlation.

Another issue arises in the variance of the observed V_{ijk}. Right skewness is common in these data, and worse yet for linear model inference, the variance of V_{ijk} increases with its magnitude. Transforming the V_{ijk} by taking logs is a typical remedy, and is suitable for some comparisons of discrete groups of measurements, but not here because it was assumed that Eq. (2) is correct. Breaking the data up into tertiles of the entire set of observed $\{V_{ijk}\}$ was considered, which would yield approximately stable variance within each tertile, and allow the use of conventional software to address correlation (such as SAS Proc Mixed; SAS, 1999). However, there are seven microenvironments in which to estimate separate concentrations, and there is interest in the fixed effects of the three communities as well. With this number of parameters, stratification by tertile left the procedure starving for data. For some VOC, the resulting estimated concentrations for certain microenvironments were negative, indicating lack of fit for this model.

To address these problems, a linear model was established with positivity constraints on the concentration parameters. Some additional notation is required:

$\mu_{(m)}$: The fixed, mean log concentration associated with the *m*th of *M* microenvironments.

s_i : The random error in log concentration associated with the subject *i*, modeled as a Gaussian random variable, $N(0,\sigma_s^2)$.

e_{ijk} : The random error in log concentration associated with subject *i*, VMP (VOC monitoring period) *j*, and replicate *k*, modeled as a Gaussian random variable, $N(0,\sigma_e^2)$.

With these effects so defined, the model for the $(i,j,k)^{th}$ measurement is given as:

$$\begin{aligned} V_{ijk} &= \sum_{m=1}^{M} \exp(\mu_{(m)} + s_i + e_{ijk}) p_{ij(m)} \\ &= \exp(s_i + e_{ijk}) \sum_{m=1}^{M} \exp(\mu_{(m)}) p_{ij(m)} \end{aligned} \quad (3)$$

Taking logs of both sides, and letting W_{ijk} denote, $\log(V_{ijk})$, one then has:

$$W_{ijk} = s_i + e_{ijk} + \log\left[\sum_{m=1}^{M} \exp(\mu_{(m)}) p_{ij(m)}\right] \quad (4)$$

The primary parameters of interest are $\mu_{(1)},\ldots,\mu_{(M)}$. The remaining parameters are σ_s^2 and σ_e^2 for the variances, and $s_1,\ldots,s_n$ for the random effects of subjects. Based on the model given by Eq. (4), an objective, hierarchical Bayesian approach was used (Berger, 1985; Berger & Wolpert, 1988), starting with uniform (flat) priors on each of $\mu_{(1)},\ldots,\mu_{(M)}$, on the precision parameters (corresponding to σ_s^2 and σ_e^2), and on each of $s_1,\ldots,s_n$. The posterior distributions of $\mu_{(1)},\ldots,\mu_{(M)}$ were approximated by the Gibbs sampling procedure (Geman & Geman, 1984; Tanner, 1996; Carlin & Louis, 2000), using 10,000 iterations for each VOC. Posterior modes (point estimates corresponding to maximum likelihood estimates with these priors) and 95%, equal-tailed credible intervals (analogous to 95% confidence intervals) were derived from these posteriors, and exponentiated to present results in the original scale ($\mu g/m^3$). These converted estimates are described as approximations of the mean concentrations for at least two reasons: First, the Gibbs procedure is based on stochastically integrating the posterior by simulation, not calculus; and second, for any random variable *X*, the mean of the log of *X* does not equal the log of the mean of *X*.

Statistical analyses were performed using SAS (SAS, 1999) and S-plus (MathSoft, 2000). Concentrations less than the method detection limit but greater than zero were included in calculations. Nondetectable measurements (i.e., samples with no analytical response or those with values of ≤0 after blank subtraction) were assigned a value of one-half the analytical detection limit (Sexton et al., 2004a, 2004b).

RESULTS

Summary statistics for measured personal exposures to 14 individual VOC are provided in Table 1. Previous publications described matched concentrations measured in indoor residential and outdoor community air, and explored relationships among personal, indoor, and outdoor samples (Sexton et al., 2004a, 2004b). The values in Table 1 are 2-d average VOC concentrations for 70 research subjects with matching time–activity (TA) data. Measurements occurred over more than 100 total days encompassing spring, summer, and fall 1999. The percentage of VOC samples with detectable measurements ranged from 76 (b-pinene) to 100% (benzene, ethyl benzene, *d*-limonene, methylene chloride, *o*-xylene, *m/p*-xylene). Arithmetic means were approximately 2–30 times higher than median values for all VOC except chloroform (50% higher) and styrene (40% higher), which indicates that distributions tended to be right skewed (or log normal).

A summary of time spent in selected microenvironments as well as time in the presence of a smoker from 2-d time–activity logs is given in Table 2. On average, study participants spent more than 89% of their time indoors; 71% (SD 17) at home; 13% (SD 15) at work or school; and 5.8% (SD 6.4) in other microenvironments. They spent an average of 6.4% (SD 7.4) outdoors, regardless of location, and 4.5% (SD 3.8) in transit. In addition, participants spent an average of 1.1% (SD 4.8) of their time in close proximity to an active smoker, irrespective of the setting.

The time diaries facilitated segregation of each 2-d VOC monitoring period into 7 exclusive microenvironments: *In-Home*—indoors at home, *In-Work/School*—indoors at work or school, *In-Other*—indoors at other than home, work, or school, *Out-Home*—outdoors at home, *Out-Work/School*—outdoors at work or school, *Out-Other*—outdoors at other than home, work, or school, and *In-Transit*—any travel from one location to another. In order to improve the ability to estimate all concentrations with the often small amounts of time reported as spent outdoors, and based on previous work suggesting these VOC are at approximately the same levels across all outdoor environments in the metropolitan area under investigation (Sexton et al., 2004a, 2004b), models were considered where the three outdoor microenvironments were combined into a single outdoor microenvironment. The resulting five microenvironments are then: In-Home, In-Work/School, In-Other, Outside (outdoors at home, work, school, or other), and In-Transit.

For each VOC, objective (flat-prior), hierarchical Bayesian models [based on Eq. (4) in the Methods section] were used to provide estimates of concentrations of each VOC by microenvironment, and for each of four variations of model complexity. These models may be labeled as follows:

7×3: Estimate concentration for each of the 7 microenvironments as recorded in the time diaries, and for each of the 3 communities.

TABLE 2
Summary of Time Spent in Seven Microenvironments and in the Presence of a Smoker from 2-Day Time–Activity Logs Maintained by Participants in the Study (n = 284)

	Hours and (% time)								
Location	Mean	SD	Min	Q10	Q25	Q50	Q75	Q90	Max
Total hours (% time)	47.9 (100)	0.5 (NA)	45.0 (NA)	47.7 (NA)	48.0 (NA)	48.0 (NA)	48.0 (NA)	48.0 (NA)	49.8 (NA)
Indoors Home	34.0 (70.9)	8.2 (17.0)	13.0 (27.1)	23.0 (48.1)	28.0 (58.3)	34.1 (71.4)	41.7 (87.1)	44.5 (92.7)	48.0 (100)
Work/school	6.0 (12.6)	7.4 (15.4)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	12.0 (25.0)	18.0 (37.5)	24.4 (52.0)
Other	2.6 (5.5)	2.9 (6.1)	0 (0.0)	0 (0.0)	0 (0.0)	2.0 (4.1)	4.0 (8.4)	6.6 (13.7)	16.6 (34.5)
Outdoors Home	1.7 (3.5)	2.4 (5.1)	0 (0.0)	0 (0.0)	0 (0.0)	0.5 (1.1)	2.5 (5.2)	5.0 (10.4)	16.3 (35.1)
Work/school	0.3 (0.6)	1.3 (2.7)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0.5 (0.9)	15.0 (31.2)
Other	1.1 (2.4)	2.1 (4.4)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1.5 (3.1)	3.9 (8.0)	15.5 (32.7)
In transit	2.2 (4.5)	1.8 (3.8)	0 (0.0)	0.5 (1.0)	1.0 (2.1)	1.8 (3.8)	2.8 (5.8)	4.2 (8.7)	12.0 (25.0)
In close proximity to a smoker[a]	0.5 (0.9)	2.1 (4.4)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0.6 (1.3)	24.2 (50.5)

Note. Results are based on 284 matched 48-h P-I-O samples with corresponding time–activity data from 70 participants.

[a]Time in the presence of a smoker could occur in any of the seven microenvironments listed above it; therefore, it overlaps with the other reported times and is not included as part of "total hours."

7×1: Estimate concentration for each of the 7 microenvironments, but without separate community effects.

5×3: Estimate concentration for each of the 5 microenvironments resulting from aggregation of the outdoor categories, and for each of the 3 communities.

5×1: Estimate concentration for each of the 5 microenvironments, but without separate community effects.

With the short times spent in the three outdoor microenvironments, and the limited available data, the three more complex models did not yield much information beyond that of the 5×1 model. Hence, the following discussion focuses on results from the 5×1 model.

Results for 14 VOC are summarized in Figure 1, where points indicate the posterior mode and brackets represent equal-tailed credible intervals. Highest estimated concentrations occurred in the In-Other microenvironments (e.g., grocery stores, restaurants, shopping malls) for 10 of 14 VOC. The four exceptions were trichloroethylene, methylene chloride, a-pinene, and chloroform. For 8 of 14 VOC, the second and third highest predicted concentrations occurred for In-Home, and In-Work/School. Estimated concentrations in the Outside microenvironment were either second or third highest for five VOC (benzene, *o*-xylene, ethyl benzene, trichloroethylene, *m/p*-xylene). The second highest predicted concentration for b-pinene occurred in the In-Transit microenvironment. Estimated concentrations in the Outside microenvironment were at or near zero for seven VOC, while estimated levels were at or near zero in the In-transit microenvironment for eight VOC. Credible intervals were largest for In-Other microenvironments for 12 out of 14 VOC, all except methylene chloride and trichloroethylene.

To get a sense of model accuracy, Figure 2 provides comparisons of model-based estimates of In-Home exposure with different measures of central tendency for approximately concurrent 2-d measurements inside residences. It is important to recognize that the posterior mode of the mean In-Home exposure estimated from the Bayesian hierarchical model is not precisely the same as the unweighted arithmetic mean of measured indoor residential concentrations. Therefore, in Figure 2, model estimates are compared to nearly coincident VOC measurements using four different measures of central tendency—median, mean, geometric mean, and squared mean of square roots. When interpreting these data it is important to keep two additional caveats in mind: The measured indoor values were not adjusted for the correlation induced by repeated measures, and measured indoor residential concentrations were 48-h averages that might not accurately represent levels encountered by participants during the time they were actually inside their homes (mean 33.9 h, range 13 to 48 h).

Because exposure to airborne VOC is a function of both concentration (Table 1) and time of contact (Table 2), it was useful to consider the relative contribution of each of the five microenvironments to cumulative personal exposure. Bar plots of mean estimated cumulative exposure over the 2-d monitoring period (predicted concentration $\times$ mean time in a particular microenvironment) are presented in Figure 3. The In-Home environment is by far the largest single contributor to cumulative personal exposure for all 14 VOC, exceeding the next largest contributor (either In-School/Work or In-Other locations) by at least a factor of 1.9 (range 1.9 for *m/p*-xylene to 11 for chloroform). The Outside and In-Transit microenvironments were estimated to be relatively minor contributors to cumulative personal exposure in all cases.

A single mixed-effects model was used to examine the effects of seven binary (yes/no) exposure conditions derived from the baseline questionnaire and/or the time–activity log that might potentially affect personal VOC concentrations: "Garage" (presence of an attached garage or any reported time in a garage or workshop); "Gasoline" (pumped gasoline or came into contact with gasoline or diesel); "Transit" (spent at least 55 min traveling on roads or highways); "ETS" (environmental tobacco smoke—tobacco products smoked inside the home or any time spent in the presence of a smoker away from home); "Water" (showering, bathing, or swimming); "Ventilation" (windows and doors in the home open >6 h/d); and "Above Median Income" (household income greater than median for participants in the study). The model mutually adjusted for all seven variables and used a hierarchical structure to account for within-subject correlation. Mean relative VOC concentrations ("yes—the condition is present" compared to "no—the condition is not present") and associated 95% confidence intervals are displayed in Figure 4. Effects on individual VOC are grouped by binary variable, and VOC are ordered by the estimated mean concentration. Statistically significant effects were found for the Garage exposure condition, which was associated with higher levels of *o*-xylene, *m/p*-xylene, benzene, ethylbenzene, and toluene, and Ventilation, which was associated with lower levels of 13 of 14 VOC (all except trichloroethylene). In addition, exposure to ETS was statistically associated with lower chloroform exposure.

DISCUSSION

A hierarchical Bayesian model was used in combination with measured personal exposures to estimate VOC concentrations in three microenvironments where independent measurements (that is, separate from the personal measurements) were not made (Indoors-at-Work/School, Indoors-in-Other locations, In-Transit) and two where independent measurements were made (Indoors-at-Home, Outside-in-the-Community). When interpreting the results of this study it is important to keep in mind several limitations of the data (Edwards et al., 2001a, 2001b; Kim et al., 2002; Sexton et al., 2004a, 2004b). First, outdoor VOC concentrations in Minneapolis–St. Paul are relatively low compared to other metropolitan areas, which

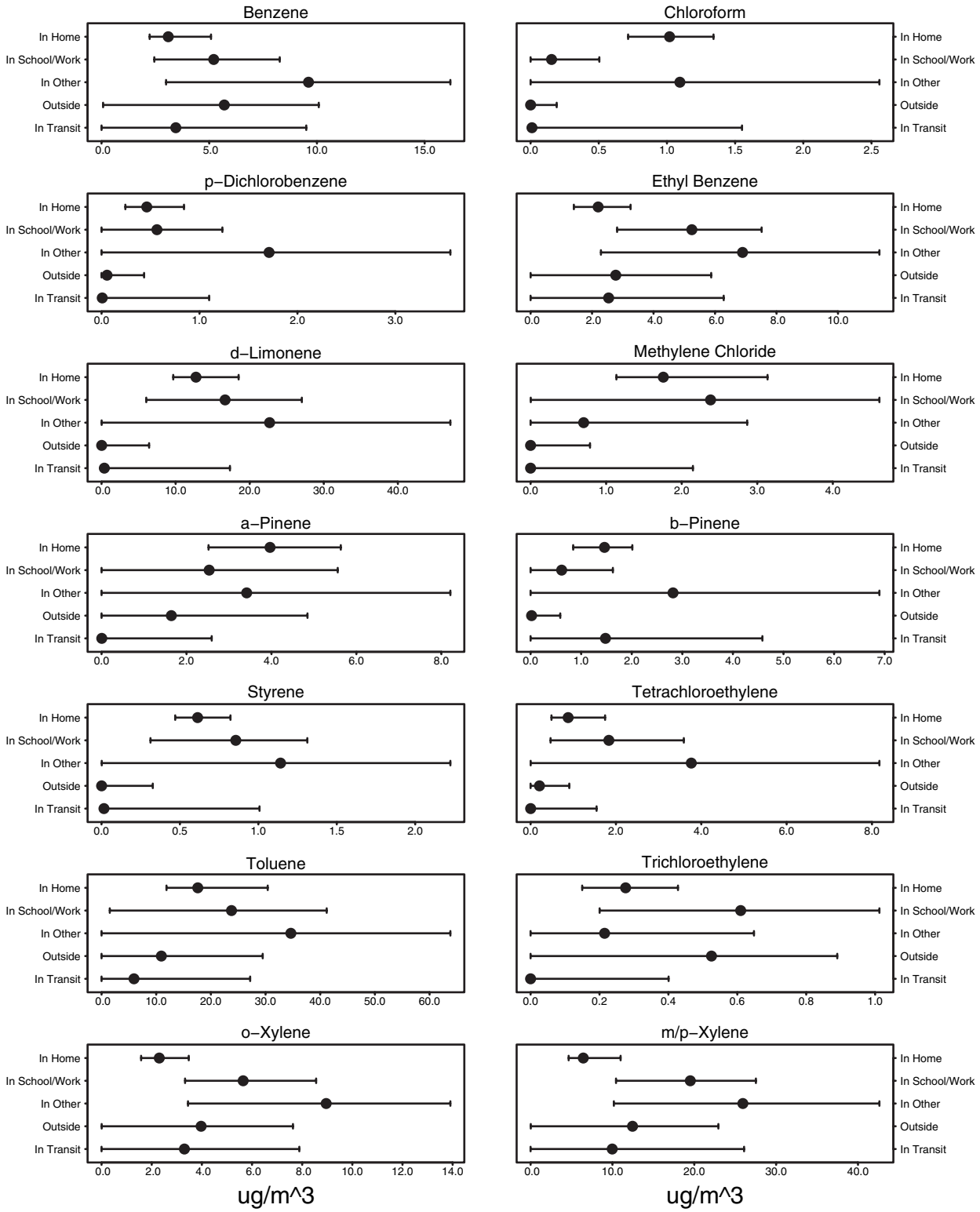

FIG. 1. Model-based estimates of VOC concentrations by microenvironment.

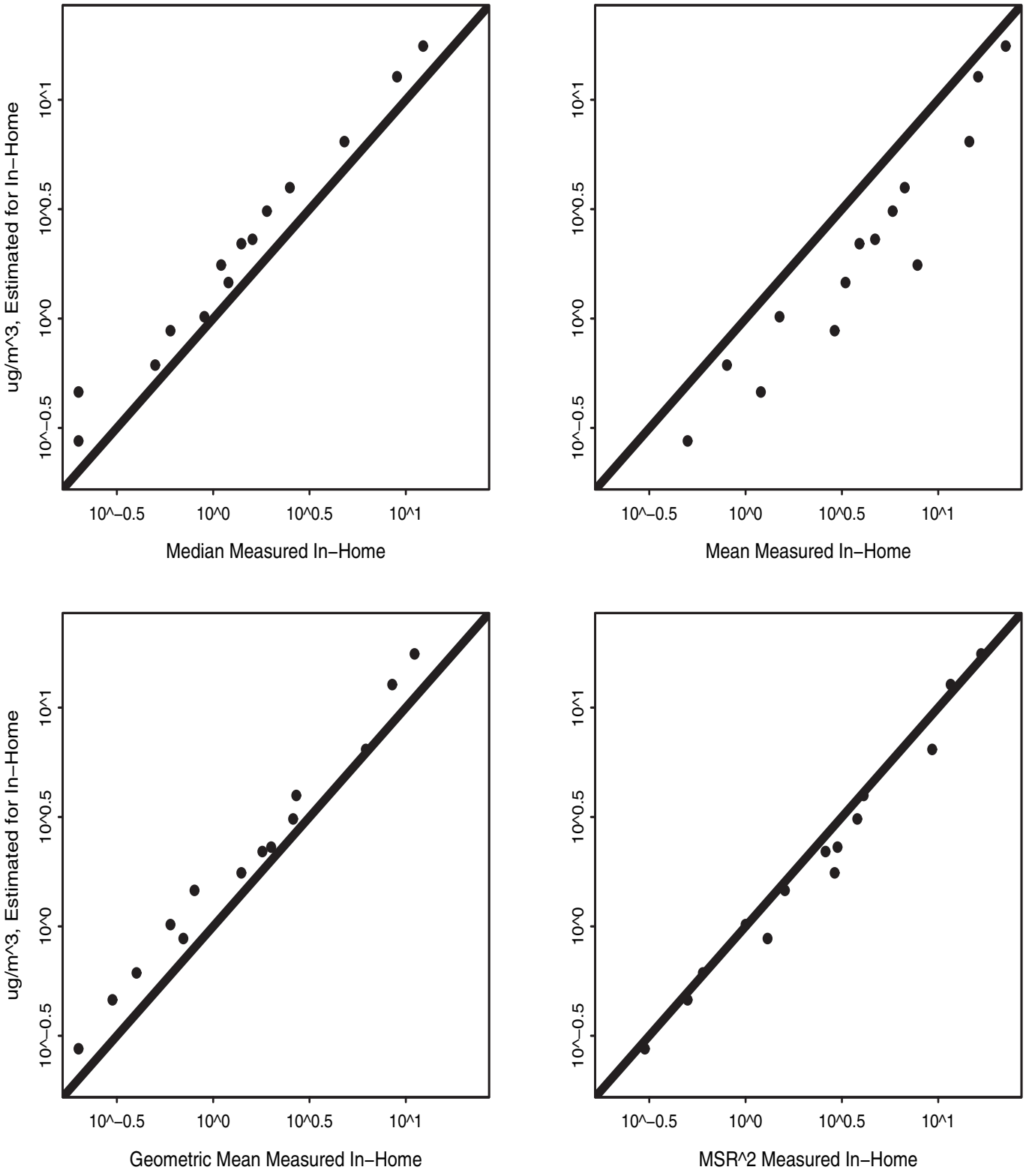

FIG. 2. Comparisons of model-based estimates of the posterior mode of indoor residential concentrations versus approximately concurrent measurements inside subjects' homes for 14 individual VOCs by four different measures of central tendency.

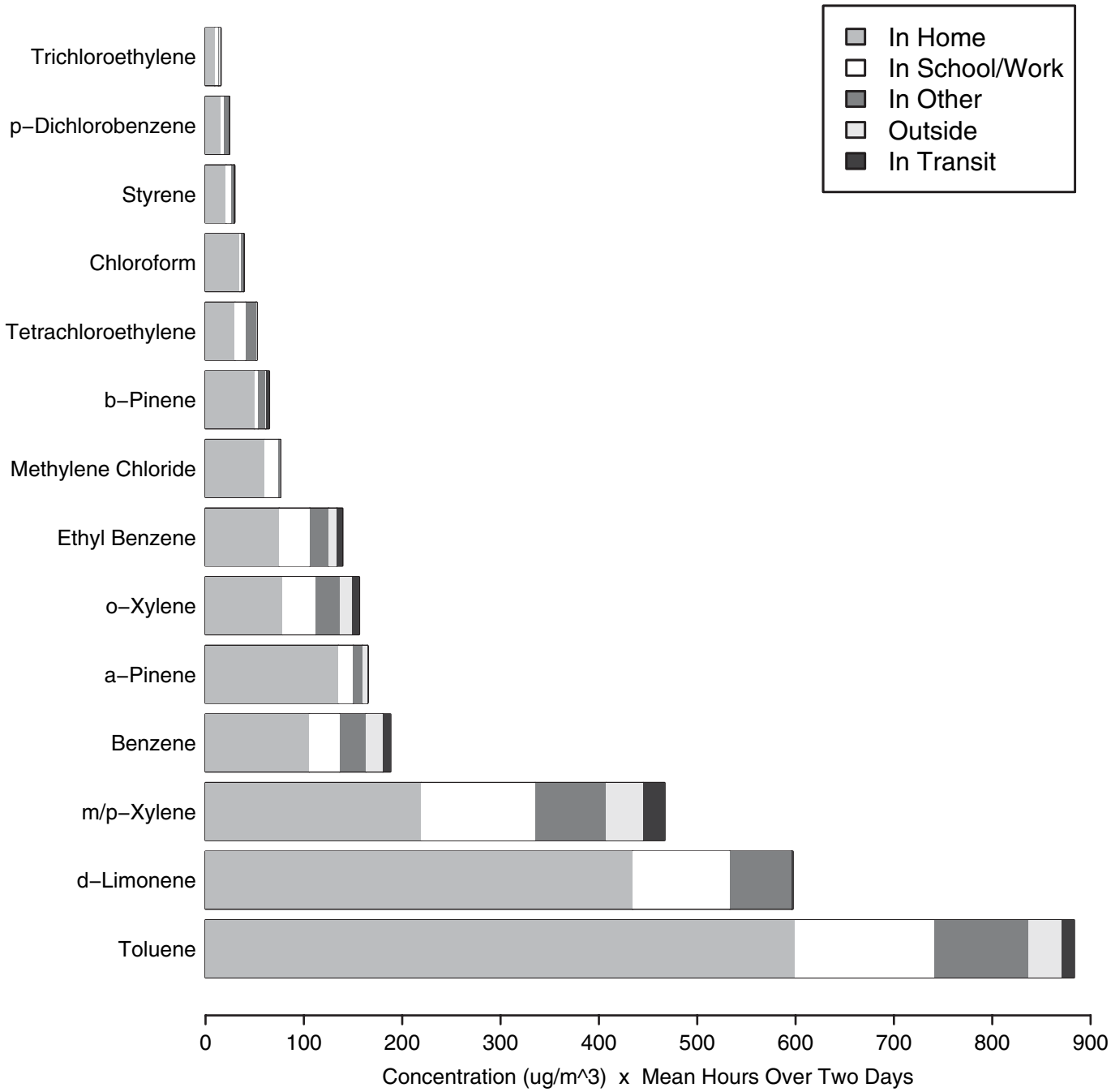

FIG. 3. Bar plot of estimated mean cumulative exposure (over 2 d) by microenvironment for 14 VOCs.

undoubtedly accounts for lower personal exposure to 13 of 14 VOC when windows and doors were left open for extended periods. Second, this is not a random sample (although households were geographically dispersed across the study areas), and the participants in the study were predominantly White, female, well educated, relatively affluent, and unlikely to be exposed to ETS at home. Third, participants may make mistakes when recording time spent in various microenvironments, which may affect modeling estimates. Fourth, measured VOC concentrations in outdoor community air and indoor residential air are 48-h averages, and may not accurately reflect concentrations when participants were actually present. Finally, the microenvironmental categories (e.g., Indoors-in-Other locations, In-Transit, Outdoors-Anywhere) are aggregate groupings, which combine diverse settings that may have dramatically different VOC concentrations.

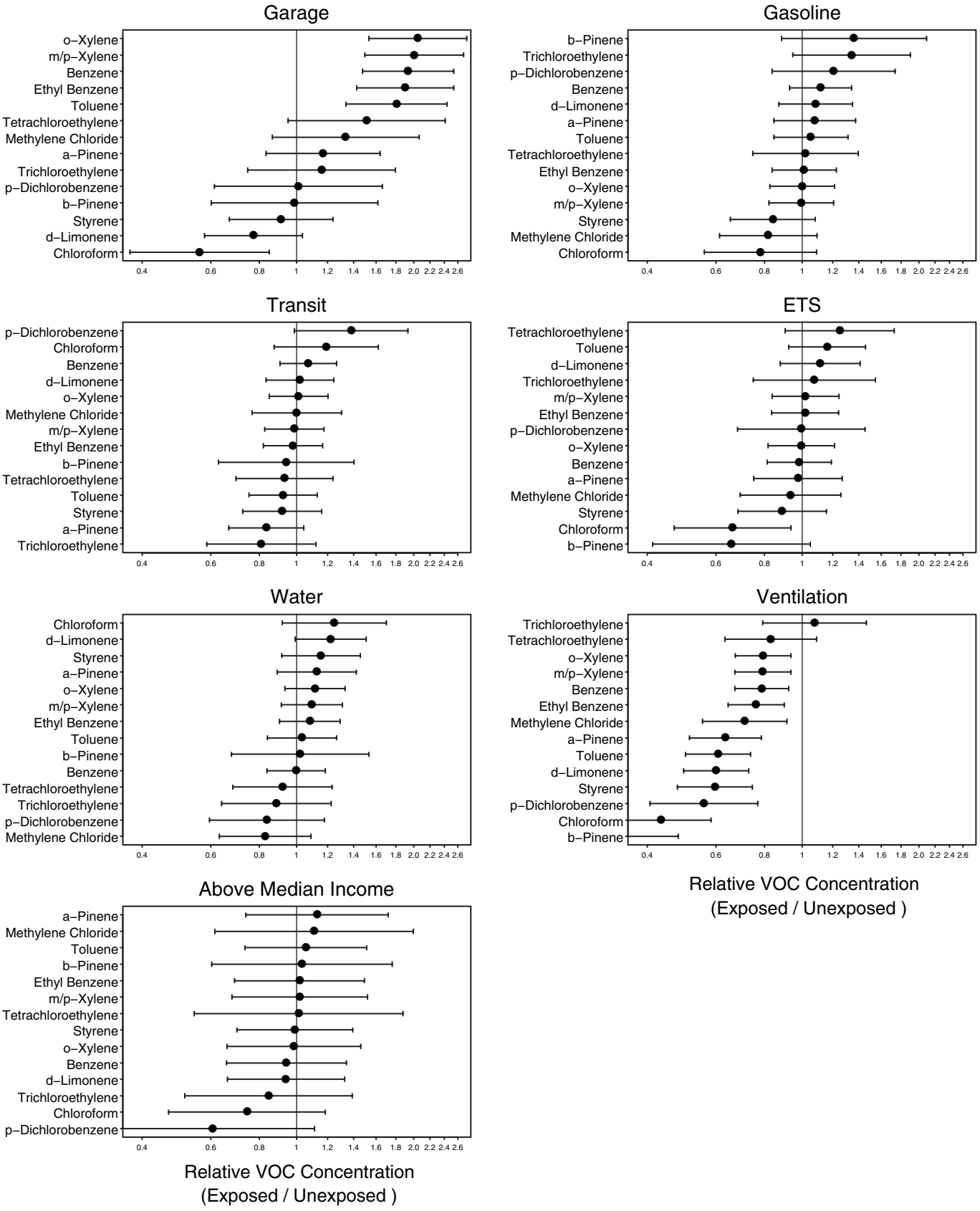

FIG. 4. Effects of binary exposure-related conditions on personal exposure to selected VOCs derived from a mixed-effects model.

Highest estimated concentrations and largest variability were associated with Indoors-in-Other settings (e.g., restaurants, shopping malls, grocery stores) for 10 of 14 VOC. Estimated levels tended to be intermediate in the Indoors-at-Home and Indoors-at-Work/School microenvironments, while estimated concentrations were negligible in the Outdoors-Anywhere and In-Transit microenvironments for 9 or 14 VOC. Comparison with measured indoor residential concentrations suggests that model-based estimates are reasonable approximations of nearly coincidental 2-day measurements.

Model results indicate that the Indoors-at-Home microenvironment was by far the largest single contributor to 2-day, cumulative personal exposure for all VOC, followed by either the Indoors-at-Work/School or Indoors-in-Other microenvironments. Conversely, the predicted contributions of Outside-Anywhere and In-Transit microenvironments were minimal for all VOC. Results suggest that airborne concentrations in two microenvironments where measurements are not routinely conducted, Indoors-at-Work/School and Indoors-in-Other locations, may be important contributors to cumulative VOC exposure.

A simple mixed-effects model was used to investigate the effects of selected binary variables likely to influence VOC exposure. Statistically significant results were obtained for two variables: higher personal exposure to 5 VOC was associated with being in or near a garage; and lower exposure to all VOC, except trichloroethylene, was associated with having windows and doors at home open >6 h for ventilation. Although a statistically significant association was also found between ETS exposure and lower exposure to chloroform, this is likely an anomalous result because there is no plausible physical explanation for an inverse link between these two variables.

Because personal monitoring is burdensome, intrusive, expensive, and frequently impractical, indirect (microenvironmental) monitoring is usually the preferred method for estimating population exposures to air pollution. It is virtually impossible, however, to measure concentrations in all potentially important microenvironments through which individuals move during day-to-day activities. In fact, most studies of nonoccupational VOC exposure measure concentrations in only two microenvironments: indoors at home and outdoors in the community. Typically these measurements are average levels over some time interval (12, 24, or 48 h) that overlaps but does not necessarily coincide exactly with the period when people are present. Results presented here suggest that this new modeling approach is a promising method for estimating VOC concentrations in seldom monitored microenvironments. Model estimates indicate that a better understanding of sources and related concentrations in work settings (e.g., offices), indoor microenvironments outside the home (e.g., restaurants, grocery stores, retail outlets), and in-transit microenvironments (e.g., inside cars and buses) may improve personal exposure estimates derived from the indirect (microenvironmental) monitoring approach.

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