Urban Air Pollution Exposure of Children in Dwight Neighborhood in New Haven, CT

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Abstract

Air pollution remains to be one of the leading causes of morbidity and mortality, especially in the urban environment. Airborne contaminants exposure differs across different communities. In the US, low-income, racial minority communities bear the burdens of high exposure and adverse health outcomes. Therefore, we conducted a study among children living in the Dwight neighborhood in New Haven, CT, where low-income immigrants and/or racial minorities reside. The objectives of the study were 1) to characterize the distribution and magnitude of individual level of airborne contaminants exposure; 2) to determine the association between environmental conditions, behavioral factors and the observed level of personal exposure. The exposure data was collected by Fresh Air wristbands, low-cost and wearable air samplers, and study participants were wearing the wristbands for five consecutive days at the end of May, 2022. 20 participants successfully returned wristbands valid for analysis. The parents/guardians of the study participants filled out a survey on household characteristics and activity patterns. From the targeted analysis, 30 chemical compounds from 10 chemical classes were detected >75% of the study participants. Chemicals detected were predominantly polycyclic aromatic hydrocarbons (PAHs) and phthalates, which are commonly found in combustion process and plasticizers in consumer products. Disparities were observed in PAHs between genders (male/female) and phthalates between race/ethnicity (Black/non-Black): female children were found to be exposed to a significantly higher level of PAHs than male children; Black children were observed to be exposed to a significantly higher level of phthalates than non-Black children. Statistically significant association between chemical exposures and behavioral factors were also observed. However, due to the limitation of sample size, the results may not be generalizable and future research is needed.

Acknowledgment

I would like to express my gratitude to my advisors Prof. Michelle Bell and Prof. Krystal Pollitt for their invaluable patience and feedback. I also could not have completed my thesis without my community partners in the Dwight neighborhood, who generously connected me with the local communities. They are Dwight residents and social workers Patricia Wallace and Jane Comins, Kristin Anderson from the Community Builders, Tamara Green from the Troupe school and Mohammad Turay from Masjid al-Islam. Additionally, this endeavor would not have been possible without the generous support from the Hixon fellowship, Environmental Justice research fellowship, Yale School of Environment & Yale School of Public Health summer funds and People, Equity and Environment microgrants, who financed my research.

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Lastly, I would be remiss in not mentioning my family, especially my parents and spouse. Their belief in me has kept my spirits and motivation high during this process. I would also like to thank my cat and dog for all the entertainment and emotional support.

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Introduction

Air pollution remains one of the leading causes of mortality globally, leading to 6.67 million premature deaths in 2019 (Murray et al., 2020). It can lead to various health issues such as respiratory infections, cardiovascular disease and lung cancer. Children and elderly persons are particularly vulnerable to air pollution exposure. Further, certain populations are more vulnerable to the hazardous environmental exposures due to more frequent or higher doses of exposure and bear a disproportionate burden of diseases. As there is more research on the vulnerable populations such as children and older populations in low and middle-income countries, there are also increasing interests in understanding the exposure and health disparities between different communities in developed countries. In the United States, Black, Indigenous and People of Color (BIPOC) community and immigrant populations, and persons with low socioeconomic status (SES) have disproportionately suffered from pollution-induced diseases. A study found that in the U.S. $PM_{2.5}$ emission is mainly caused by White persons due to higher consumption of goods and services, while racial/ethnic minority populations are exposed to higher $PM_{2.5}$ concentration, particularly the Black and Hispanic communities (Tessum et al., 2019). Research suggests that Hispanic and Black children are exposed to higher levels of air pollution compared to White children, and many of them are exposed more at home than at school, and they have higher incidence of childhood asthma (Chakraborty and Zandbergen, 2007; Forno and Celedón, 2012).

A variety of volatile organic compounds (VOCs) and semi volatile organic compounds (SVOCs) are detected in the indoor environment due to the natural release of building materials, the use of consumer products and indoor activities such as cooking and smoking (Allen et al., 2007; Demirtepe et al., 2019; Farmer et al., 2019; Lucattini et al., 2018). Moreover, individuals spend over 90% of their time indoors and a long time of exposure (US EPA, 2017). Children traditionally spend more time outdoors compared to adults, while due to the prevalence of electronic devices and the COVID-19 pandemic, the time they spend outdoors decreases. A Canadian study suggested that 63.8% children who participated in the study spent less time in outdoor physical activities such as walking or biking or other outdoor sports and 47.5% of the children spent less time in outdoor playing during the pandemic (Mitra et al., 2020). In comparison, the same study also found that there was an increase of 31.2% in indoor physical activities or sports and an increase of 61.0% in indoor playing. Furthermore, a number of research indicates indoor air pollution can lead to multiple adverse health outcomes such as cardiovascular and respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD), degrading cognitive function, or even lung cancer (Prüss-Üstün et al., 2016). It is estimated that in developing countries, around 250 million children fail to reach their developmental potential because of exposure to environmental pollution (Black et al., 2017). Children are exposed more to certain groups of organic chemicals such as flame retardants than adults (Butt et al., 2016; Cowell et al., 2017; Gibson et al., 2019). Therefore, it is important to understand the personal level of air pollution exposure on children, which is critical for their future growth and development.

As technologies for air pollution exposure assessment advance, portable or wearable exposure devices have appeared as a useful tool for personal exposure assessment studies (Allen et al., 2007; Craig et al., 2019; O'Connell et al., 2014). Silicone wristbands were first used in 2014 and attracted a wide range of research interests and these passive samplers have been employed in over 30 epidemiological studies (Kile et al., 2016; Lipscomb et al., 2017). Similar to the silicone wristbands with their non-invasiveness and low burden, the Fresh Air wristband emerged recently to measure personal exposure to various SVOCs and VOCs, pesticides, phthalates, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and poly-brominated diphenyl ethers (PBDEs) (Koelmel et al., 2021c; Lin et al., 2020). The availability of these low-cost, non-invasive, wearable air pollution samplers allows researchers to determine air pollution exposure to vulnerable populations such as children and the elderly more accurately.

Besides the wearable air samplers, gas chromatography high-resolution mass spectrometry (GC-HRMS) can not only determine the magnitude, frequency and distribution of relatively well-known chemicals, but also screen for thousands of unknown chemicals (Koelmel et al., 2021b). After chemical characterization based on screening, toxicity of the detected chemical compounds can be classified using experimental or computational evidence (Aksenov et al., 2020; Vegosen and Martin, 2020; Williams et al., 2017).

Given the adverse health impacts of childhood air pollution exposure and ongoing exposure disparity, the objective of the study was to identify behavioral factors and household characteristics that affect the observed variance in the chemical exposure to children living in a low-income neighborhood in a racially segregated city – Dwight neighborhood in New Haven, CT. Furthermore, the study results were reported back to the community and also provide useful information for policy-makers and future research studies.

Materials and Methods

Study Population and Recruitment

The study design includes five stages: participant recruitment, online/paper survey, air pollution exposure measurement, data analysis, and reporting results back to the community. Inclusion criteria of study subjects includes having an age between 2 to 16 years and residence in the Dwight neighborhood in New Haven, CT for at least a year by the time of participant recruitment. Recruitment began in early May 2022 and continued until the end of May 2022. Recruitment flyers were written in English, and translated into Spanish, Arabic and Pashto. The participants were recruited through Community Builders, a local community organization that manages over 200 apartments in the neighborhood; Troupe School, a local school in the neighborhood; and Masjid al-Islam, a local mosque; and some participants were recruited in person in the neighborhood. In total, 43 participants were recruited and asked to wear the Fresh Air wristbands for 5 consecutive days. Their parents or primary caregivers were asked to complete an online/paper survey on daily routines and household characteristics to indicate potential pollutant sources. However, possibly due to the young age of some participants, 16 participants lost their wristbands during swimming or at school, 5 participants lost contact in the middle of the study, and 2 participants' samples were contaminated and not valid for analysis. Therefore, 20 wristband samples were successfully returned and analyzed. 2 field blank samples were also analyzed as a reference level. All participants who successfully returned the wristbands were offered a $10 gift card in exchange for the participation. At the end of the study, all participants were also offered both the overall and individual study results and a brochure on clean air issued by the Environmental Protection Agency (EPA) (US EPA, 2014). The study was approved by the Institutional Review Boards from Yale University. The parents or primary caregivers of the children provided electronic consent prior to participating in the study and the children provided verbal assent.

Survey of Potential Pollutant Sources

A Qualtrics survey was designed to identify potential air pollution sources (e.g. smoking, cooking frequency, stove type and use of ventilation) and to determine the degree how participants were affected (e.g. the time they are around cooking activity, time spent outdoors). The survey also collected information on the demographic information, family, household characteristics, daily activities, and existing health concerns, and included an open-ended question for additional concerns and comments. The parents or primary caregivers of the participants completed the survey prior to the deployment of the wristbands. The survey was originally designed in English, and translated to Spanish, Arabic and Pashto to accommodate different language needs of Dwight neighborhood residents. The survey was mainly conducted on electronic devices, while printout paper surveys were used by several participants based on their preferences.

Air Pollution Exposure Measurement

Fresh Air wristbands contain a band embedded with a polytetrafluoroethylene (PTFE) chamber, which consist of four fabricated polydimethylsiloxane (PDMS) sorbent bars to absorb airborne chemicals passively (Guo et al., 2021). Prior to deployment, PDMS sorbent bars were fabricated manually and cleaned under 300ºC in a vacuum cleaner for 2 hours (Guo et al., 2021; Koelmel et al., 2021c; Lin et al., 2020). After deployment at the end of May 2022, participants were requested to wear the wristbands for 5 consecutive days and remove them during showering, or swimming. At the end of the exposure assessment, study staff collected the Fresh Air wristbands and stored them in well-sealed glass containers. The samplers were stored in a -20 ºC refrigerator before analysis.

Chemicals collected from the wristbands were analyzed using gas chromatography high resolution mass spectrometry (GC-HRMS). The analytes were absorbed by the PDMS, extracted by thermal desorption and volarized in the GC-HRMS. Data processing included spectral deconvolution and identification, targeted peak detection and alignment in Compound Discoverer 3.2 (Thermo Fisher Scientific, Waltham, MA), used for suspect screening to determine relative abundances and potential identifications of compounds across participants (Koelmel et al., 2021a). TraceFinder 4.1 (Thermo) was used to analyze raw mass spectral data and a total of 70 compounds was quantified (Guo et al., 2021). Blank feature filtering (BFF) was conducted to remove compounds with high background contamination (Patterson et al., 2017). Manual validation was also performed to reduce false positives. Moreover, for identified compounds, predicted toxicities such as mammalian acute toxicity, mutagenicity and developmental toxicity was used to highlight the compounds of concern (Benfenati et al., 2009; Cassano et al., 2010; Sushko et al., 2010).

Fresh Air wristbands measure 37 chemicals using targeted methods and 474 chemicals through a nontargeted approach in this study, including nicotine, homosalate, and chloroaniline, which are commonly found in cigarettes, skincare products and industrial products. These pollutants were selected due to their prevalence in the human living environment and potential health concerns.

Statistical Analysis

To understand correlation between targeted chemical compounds and chemical classes, the Spearman's correlation was calculated. After transformation, the majority of the chemical exposures did not have a normal distribution. The R package *chorddiag* was used to demonstrate inter-class correlations.

For exposome data analysis, the R package *rexposome* was used to understand exposome data such as quantification of missing data, individual clustering and determination of the association between activity patterns and exposures (Carles Hernandez-Ferrer, 2023). Exposome is considered as the measurement of exposures of individuals, and the data was loaded in "description", "exposures" and "phenotype" files. Exposure characterization was explored using the function *plotFamily,* such as the association between stove type or cooking frequency and polycyclic aromatic hydrocarbons (PAHs) exposure, smoking activities and nicotine exposure, indoor time and phthalate exposure etc. Individuals clustering analysis was conducted using the *clustering* function to obtain the classification of chemical exposure to each individual. Principal component analysis (PCA) was also performed to evaluate variance across the detected chemical components as well as their association with different phenotypes.

Reporting Results back to the Community

At the end of the study, every participant was offered both the overall and individual study results and a brochure on indoor air quality issued by EPA (US EPA, 2014). The study results consist of their individual exposure level and the average overall level of the study subjects.

Results

Study Participants Characteristics

For the participants who successfully returned wristbands valid for analysis (20/43), their details are listed in Table 1. Of the 20 participants, their average age at time of recruitment was 9.85 years old and half of them were female. Around 50% of the participants were Black/African American, 20% of the participants of Hispanic, Latino or of Spanish origin, one participant was Central Asian, and one was White/European American. Over half of the participants were from low-income (<$15k per year) compared to New Haven average ($42,000 per year) (City data, 2023), large households (>5 people per household). Over half of the participants had one or both parents completed high school education without a bachelor degree.

For activity patterns, 65% of study participants were from households that cooked >3 times a day, 10% cooking 2-3 times/day and 25% cooking 0-1 time/day. 75% of the houses were equipped with electric stove and 25% with gas stove. All households reported that they used ventilation when cooking. Over half of the study participants walked to school and the remainder went by bus or bike. 60% of the participants spent less than 15 minutes each way commuting to school one-way and 65% of the participants spent 5-10 hours/week outdoors. Moreover, 45% of the participants lived with a smoker and 55% of the children had bedrooms that faced major traffic roads.

Table 1
Study participant and household characteristics (N=20)

	Overall (N=20)
Age (years)	
Mean (SD)	9.85 (4.15)
Median [Min, Max]	9.50 [2.00, 17.0]
Gender	
Female	10 (50.0%)
Male	10 (50.0%)
Race/Ethnicity	
Asian (Central Asian)	1 (5.0%)
Black or African American	9 (45.0%)
Mixed-race: Black or African American; Native Hawaiian or other Pacific Islander	5 (25.0%)
Hispanic, Latino or of Spanish origin	4 (20.0%)
White or European American	1 (5.0%)
Household Size (number of people)	
>5	8 (40.0%)

	Overall (N=20)
2	2 (10.0%)
3	4 (20.0%)
4	1 (5.0%)
5	5 (25.0%)
Highest Education Level of One or Both Parents	
High school graduate, diploma or the equivalent (for example: GED)	14 (70.0%)
Trade/technical/vocational training	1 (5.0%)
Bachelor’s degree	5 (25.0%)
Graduate degree	0 (0%)
Household Income Level (annual)	
None	2 (10.0%)
$1 to $10,000	4 (20.0%)
$10,000 to $14,999	10 (50.0%)
$15,000 to $24,999	2 (10.0%)
$25,000 to $34,999	1 (5.0%)
$35,000 to $49,999	1 (5.0%)
Parents Employment Status	
Full-time	11 (55.0%)
Part-time	5 (25.0%)
Unemployed	4 (20.0%)
Living with a Smoker at Home	
No	11 (55.0%)
Yes	9 (45.0%)
Stove Type	
Electricity	15 (75.0%)
Gas	5 (25.0%)
Cooking Frequency	
>3 times per day	13 (65.0%)
2-3 times per day	2 (10.0%)
0-1 time per day	5 (25.0%)
Bedroom Facing Traffic Road(s)	
No	9 (45.0%)
Yes	11 (55.0%)
Ways to Commute to School	
Biking	1 (5.0%)

	Overall (N=20)
Public transportation (e.g. bus)	8 (40.0%)
Walking	11 (55.0%)
Commuting Time to School, One Way	
<15 minutes	12 (60.0%)
15-30 minutes	2 (10.0%)
30-45 minutes	6 (30.0%)
Time Spent Outdoors	
<5 hours per week	3 (15.0%)
10-20 hours per week	4 (20.0%)
5-10 hours per week	13 (65.0%)

Chemical exposures across participants

After chemical analysis of the wristband samplers, 37 compounds were measured, including pesticides and herbicides, VOCs, pyrethroids and related, flame retardants and smoke-related chemicals. Among these 37 chemicals, 1,4-dichlorobenzene, triphenyl phosphate (TPHP), benz[a]anthracene, hexachloroethane, piperonyl butoxide, anthracene and hexachlorobutadiene were excluded due to detection in <75% of samples (Figure 1).

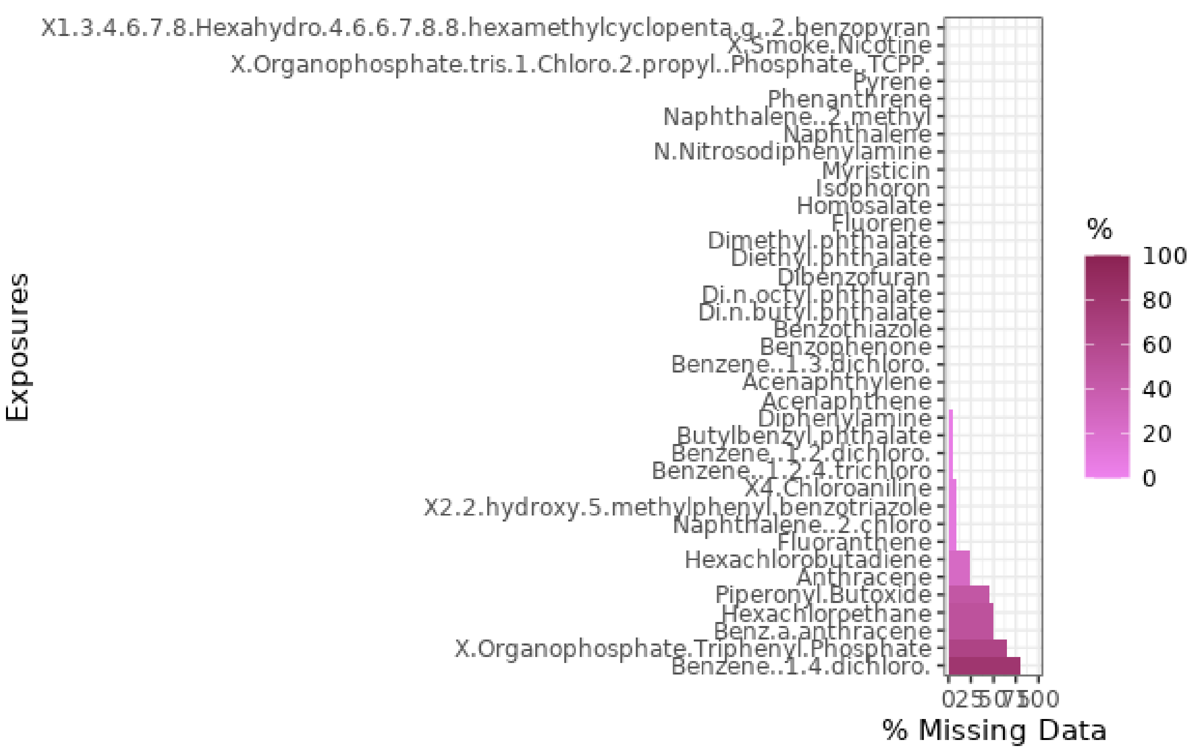


Figure 1. Missing data in targeted analysis

In total, 30 chemicals were considered for further analysis, including 13 polycyclic aromatic hydrocarbons (PAHs), 5 phthalates, 2 organochlorine pesticides, 2 VOCs, 3 nitroaromatics and isophorones, 1 smoking related chemical, 1 aromatic hydrocylic compound (AHC), 1 plant volatile compound, 1 organophosphate ester (OPE) flame retardant, and 1 nitrosamine (Figure 2). Overall, nitroaromatics and isophorones was detected to be the highest: homosalate with a median of 16.64 pg/m^3 per day (Q1 to Q3: 14.69 to 18.25), isophoron with a median of 13.70 pg/m^3 per day (Q1 to Q3: 13.17 to 17.22) and 4-chloroaniline with a median of 13.38 pg/m^3 per day (Q1 to Q3: 12.40 to 15.15). Organochlorine pesticides were the lowest detected mass, ranging from a median of 1.025 pg/m^3 per day (Q1 to Q3: 0.7138 to 1.641) for naphthalene, 2-chloro to a median of 4.417 pg/m^3 per day (Q1 to Q3: 3.162 to 4.959) for benzene, 1,2,4-trichloro. The median exposure levels of phthalates ranged from 10.44 pg/m^3 per day (Q1 to Q3: 8.730 to 14.21) for butylbenzyl phthalate, 12.47 pg/m^3 per day (Q1 to Q3: 11.36 to 14.11) for di-n-butyl phthalate, 14.45 pg/m^3 per day (Q1 to Q3: 8.844 to 15.54) for di-n-octyl phthalate, 15.27 pg/m^3 per day (Q1 to Q3: 14.43 to 16.85) for dimethyl phthalate and 17.48 pg/m^3 per day (Q1 to Q3: 16.50 to 19.11) for diethyl phthalate. The median exposure for PAHs was the highest for galaxolide (1,3,4,6,7,8-hexahydro-4,6,6,7,8,8,-hexamethyl-cyclopenta[g]benzopyran) (median: 18.23 pg/m^3 per day, Q1 to Q3: 17.51 to 18.65), and lowest for fluoranthene (8.137 pg/m^3 per day, Q1 to Q3: 7.961 to 8.382).

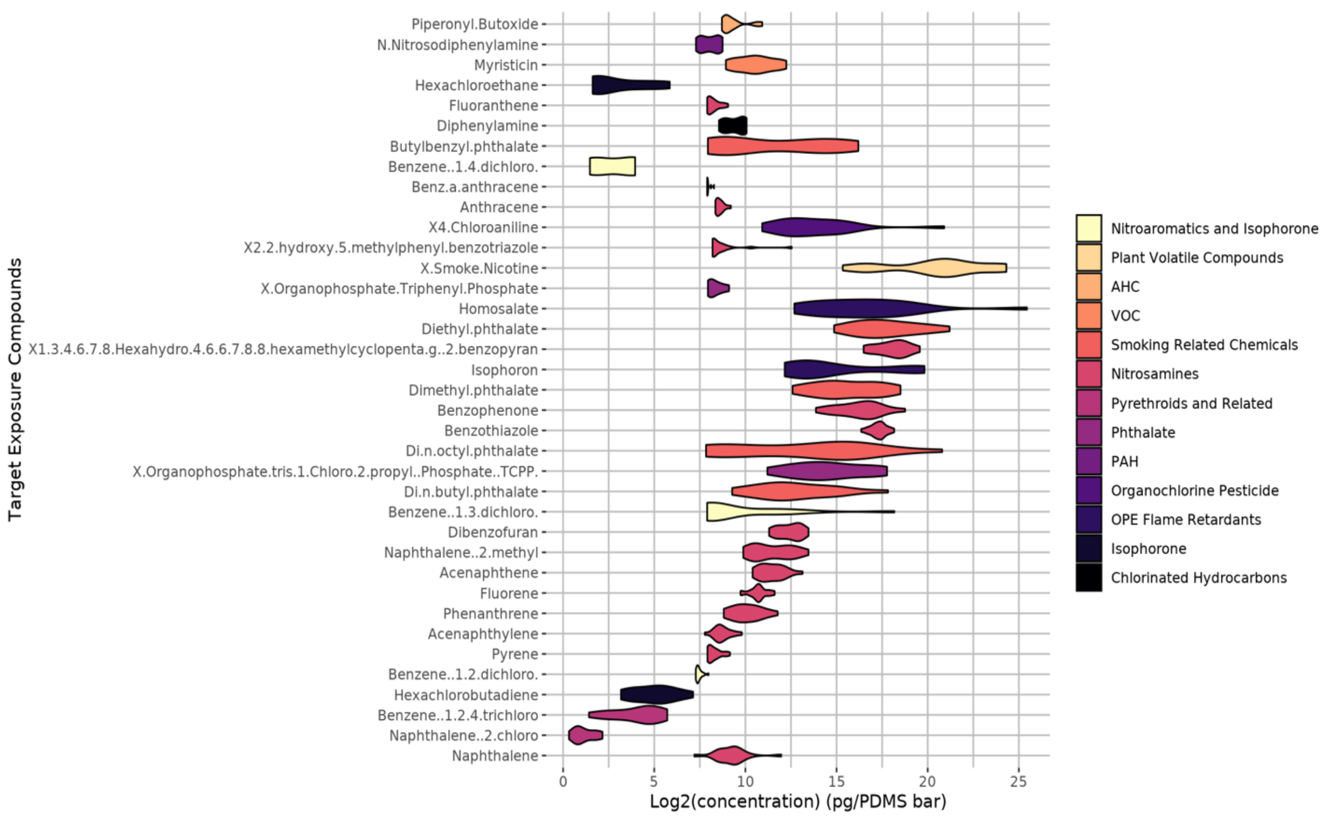


Figure 2. Targeted exposure compounds among study participants in Dwight neighborhood in New Haven, CT.

Exposure characteristics and correlations

Both intra- and inter-correlations between different exposure compounds across all 10 chemical classes are shown in Fig. 3. There were 450 unique pairwise correlations in total, and 44 were considered as statistically significant ($p < 0.05$). Some chemicals were highly correlated within the same chemical class. For PAHs chemicals, several chemicals were highly correlated, such as pyrene and phenanthrene, pyrene and fluoranthene, phenanthrene and fluoranthene, pyrene and 2-2-hydroxy-5-methylphenyl, benzotriazole with average correlation coefficients of 0.89, 0.97, 0.9 and 0.78 respectively. For phthalates, Di-n-octyl phthalate and Di-n-butyl phthalate were highly correlated with a correlation coefficient of 0.97. For the two VOC compounds, 1,2-dichlorobenzene and 1,3-dichlorobenzene were correlated with a correlation coefficient of 0.63. Moreover, for inter-correlations between chemicals from different chemical classes, PAHs and phthalates were significantly correlated with nitroaromatics and isophorone during the study period. The carcinogenic N-nitrosodiphenylamine and less hazardous diphenylamine, 2-2-hydroxy-5-methylphenyl, benzotriazole and 4-Chloroaniline were also highly positively correlated. Both pairs had a correlation coefficient of 0.99. On the other hand, several chemicals were negatively correlated. 2-Methylnaphthalene was negatively correlated with various chemicals including N-nitrosodiphenylamine, diphenylamine, PAHs and phthalates such as fluoranthene, pyrene, dimethyl phthalate and butylbenzyl phthalate, with correlation coefficients of -0.67, -0.73, -0.61, -0.61, -0.54 and -0.53 respectively.

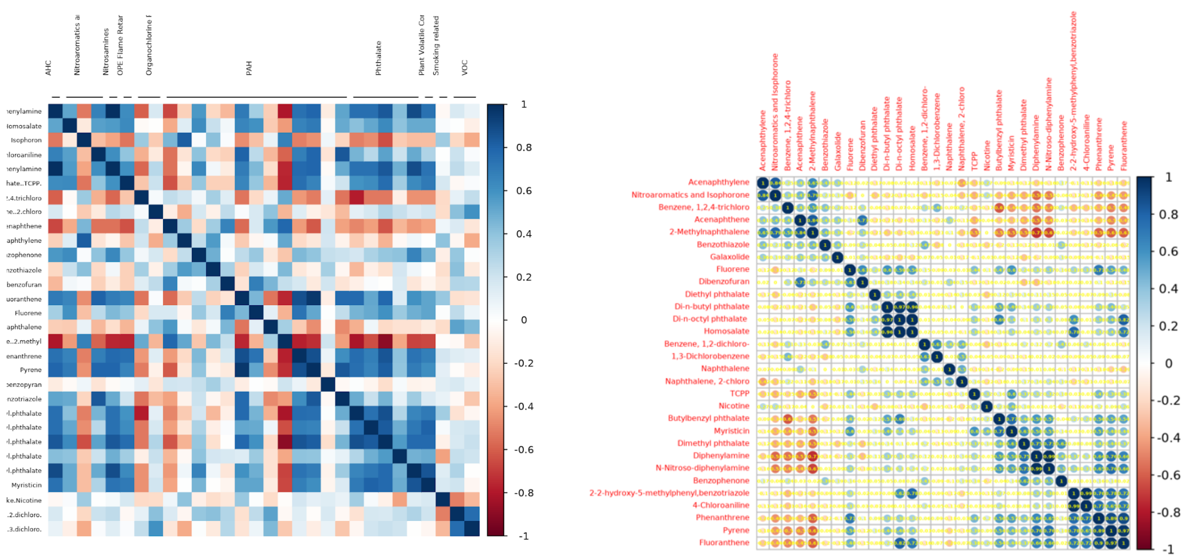


Figure 3. Targeted exposure compounds correlation plot.

Detected Chemical Exposures across Participants

Results suggest potential gender and racial disparity in certain chemical classes, although findings are not statistically different. In general, female children were found to have higher chemical exposures than male children (Figure 4), and PAHs such as naphthalene and pyrene, commonly found in burning coal, gasoline and tobacco, showed significant gender difference

(Figure 4B). No statistically significant gender disparity was found across other chemicals and there was no exposure difference found between boys and girls in phthalates, VOC and organochlorine pesticides (Figure 4A, D&F), although the small sample size hinders such analysis. For race and ethnicity exposure differences, due to limited sample size, all non-Black participants (White, Hispanic or Latinx, Asian, Mixed-race) were grouped together as non-Black participants. Black or African American participants were found to be exposed to higher levels of phthalates, PAHs, VOCs, AHC, plant volatile compounds, nitrosamines and OPE flame retardants compared to non-Black participants (Figure 5). Elevated level of exposure in the phthalates such as dimethyl phthalate, diethyl phthalate and butylbenzyl phthalate, mainly from personal-care products and fast foods, were found to be significantly higher in Black participants (Figure 5A). There was no exposure difference observed in VOC, nitroaromatics and isophorone, organochlorine pesticides between Black and non-Black participants.

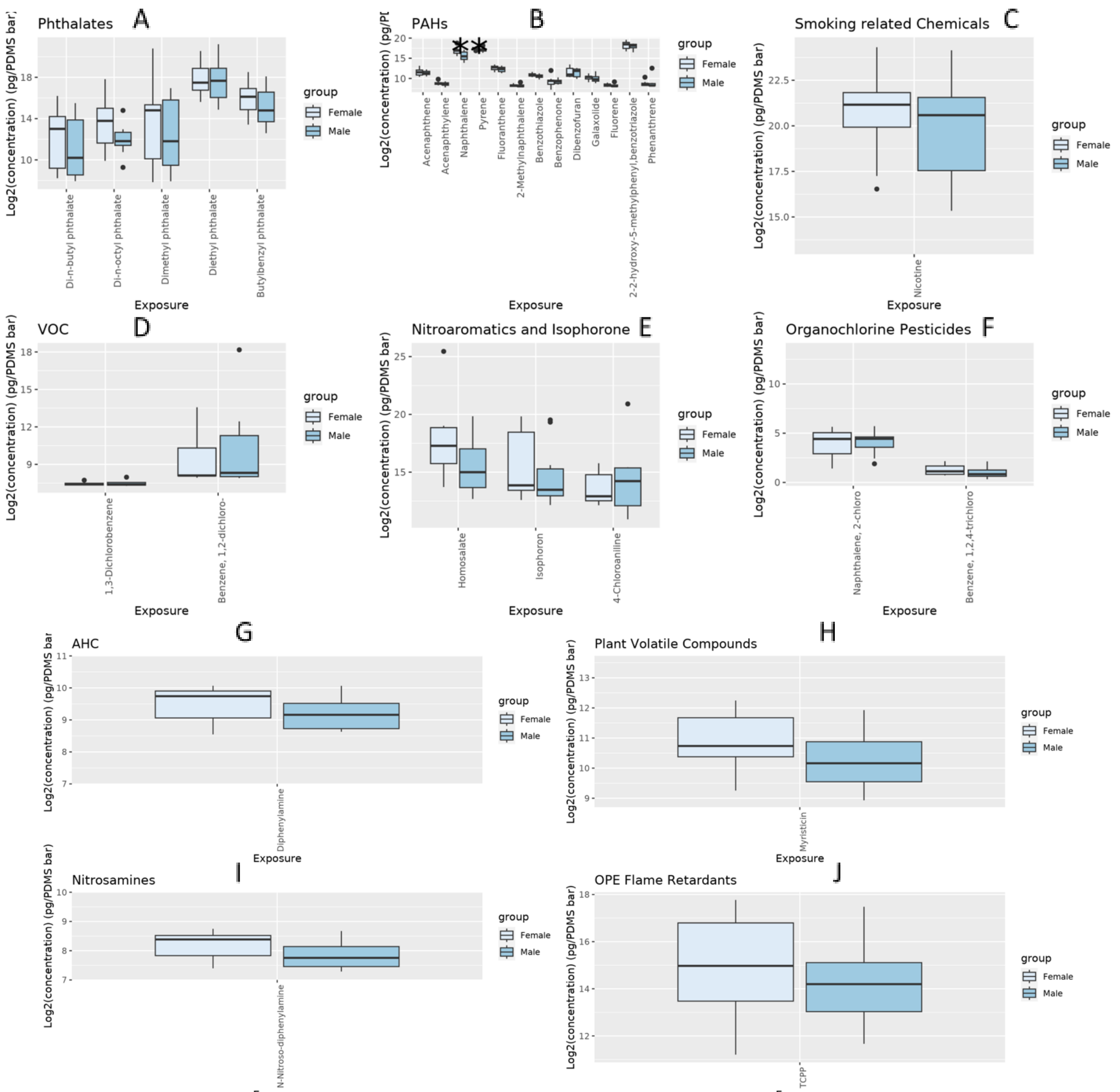


Figure 4. **Chemical exposures by gender.**

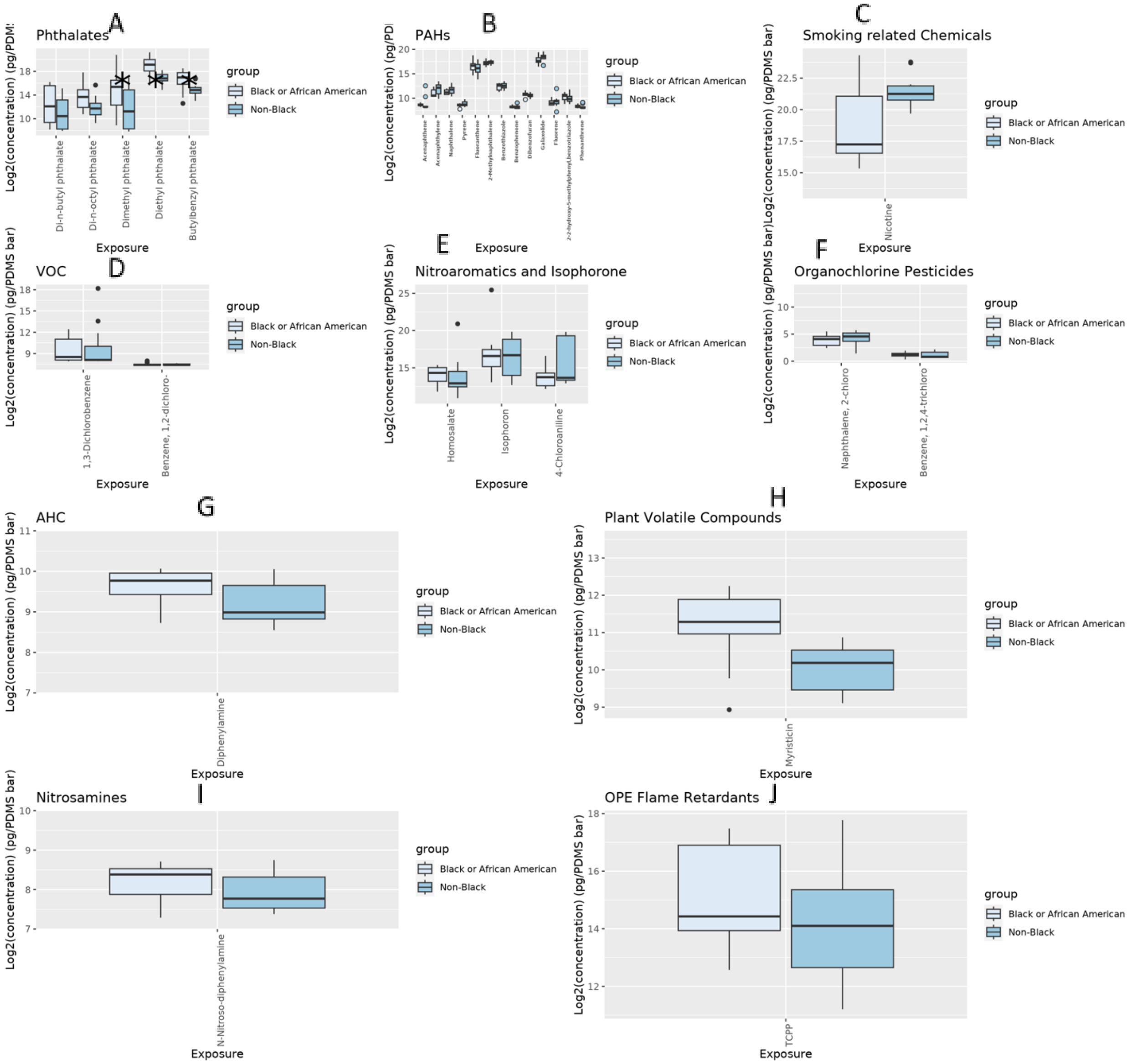
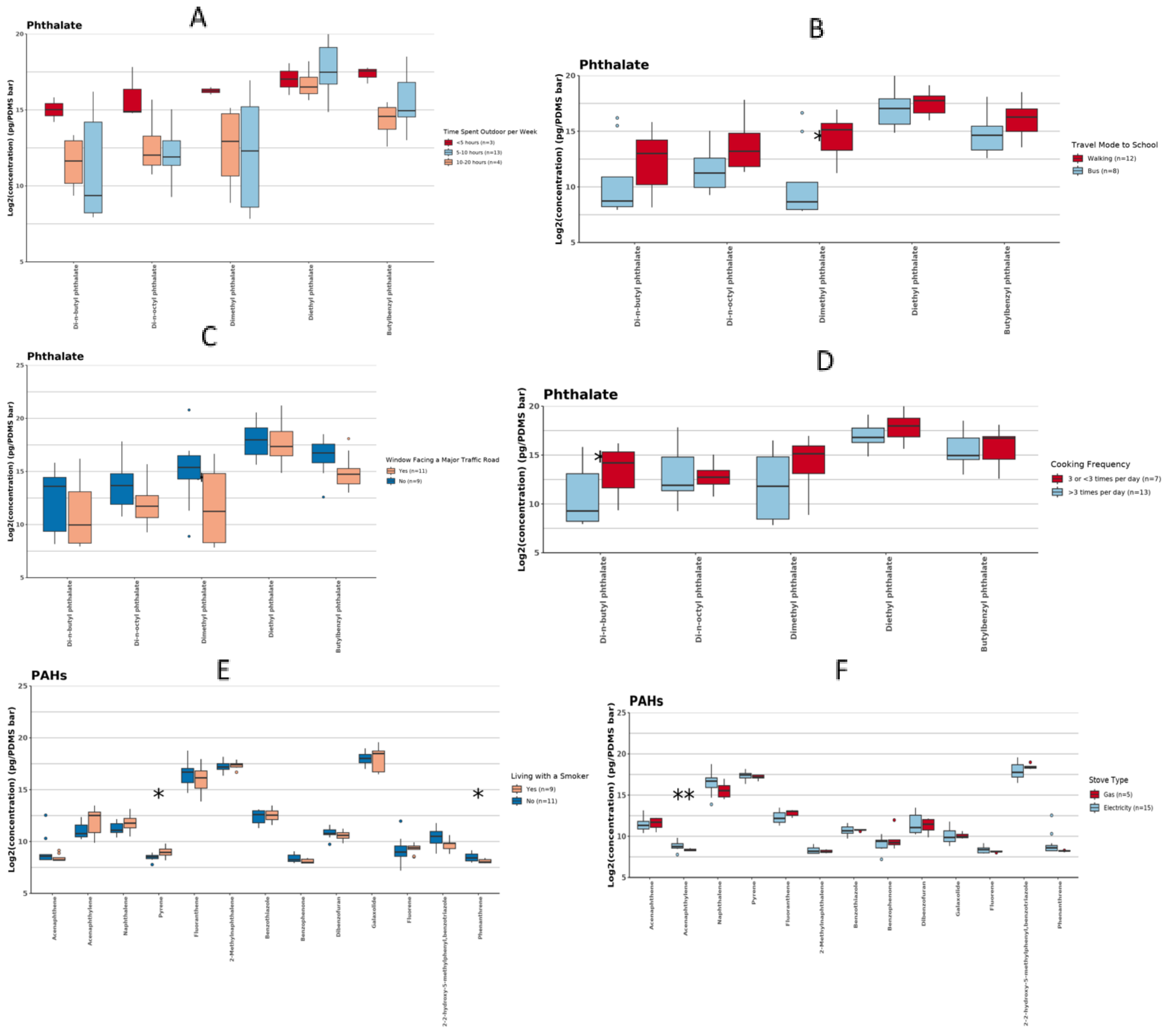


Figure 5. **Chemical exposures by race/ethnicity.**

The results also suggested certain household characteristics and activity patterns affected the level of exposure in the study cohort. Certain chemicals are closely related to the traffic and cooking emissions. For phthalates, children spent time indoor had a higher level of exposure compared to children spent more time outdoors (Figure 6A); children walking to school were exposed to a higher overall level of phthalates compared to those taking a bus to school, and dimethyl phthalate exposure was significantly higher (Figure 6B); children living in bedrooms with windows facing traffic roads were exposed to higher level of phthalates than those in bedrooms with no window or window not facing any traffic roads, and dimethyl phthalate exposure was found to be significantly higher (Figure 6C); interestingly, for cooking frequency, less cooking indicated a higher exposure of phthalates, in which di-n-butyl phthalate was statistically significantly higher (Figure 6D). There are many factors affecting the PAHs exposure. Participants who were living with a smoker were exposed to higher levels of PAHs and the exposure disparity for pyrene was demonstrated to be statistically significant (Figure 6E); for cooking, electricity stove was associated with a higher exposure of acenaphthylene and more frequent cooking activities was related to a higher exposure of PAHs (Figure 6 F&G); overall, walking to school was associated with a higher exposure of PAHs chemicals such as 2-methylnaphthalene, benzothiazole, galaxolide and fluorene, while acenaphthylene and dibenzofuran were found to be significantly higher in children taking bus to school (Figure 6H). For the exposure of two VOC chemicals, children from houses with a gas stove, children who spent more time outdoors and children walking to school were found to be exposed to higher levels of 1,2-dichlorobenzene (Figure 6I, J&K). Children living with a smoker and spending more time indoors were exposed to a higher level of nicotine, while the differences were not statistically significant (Figure 6 M&N). For nitroaromatics and isophorone, children spending 5-10 hours outdoors per week and taking a bus to school were exposed to significantly higher levels of isophorone (Figure 6 O&P).



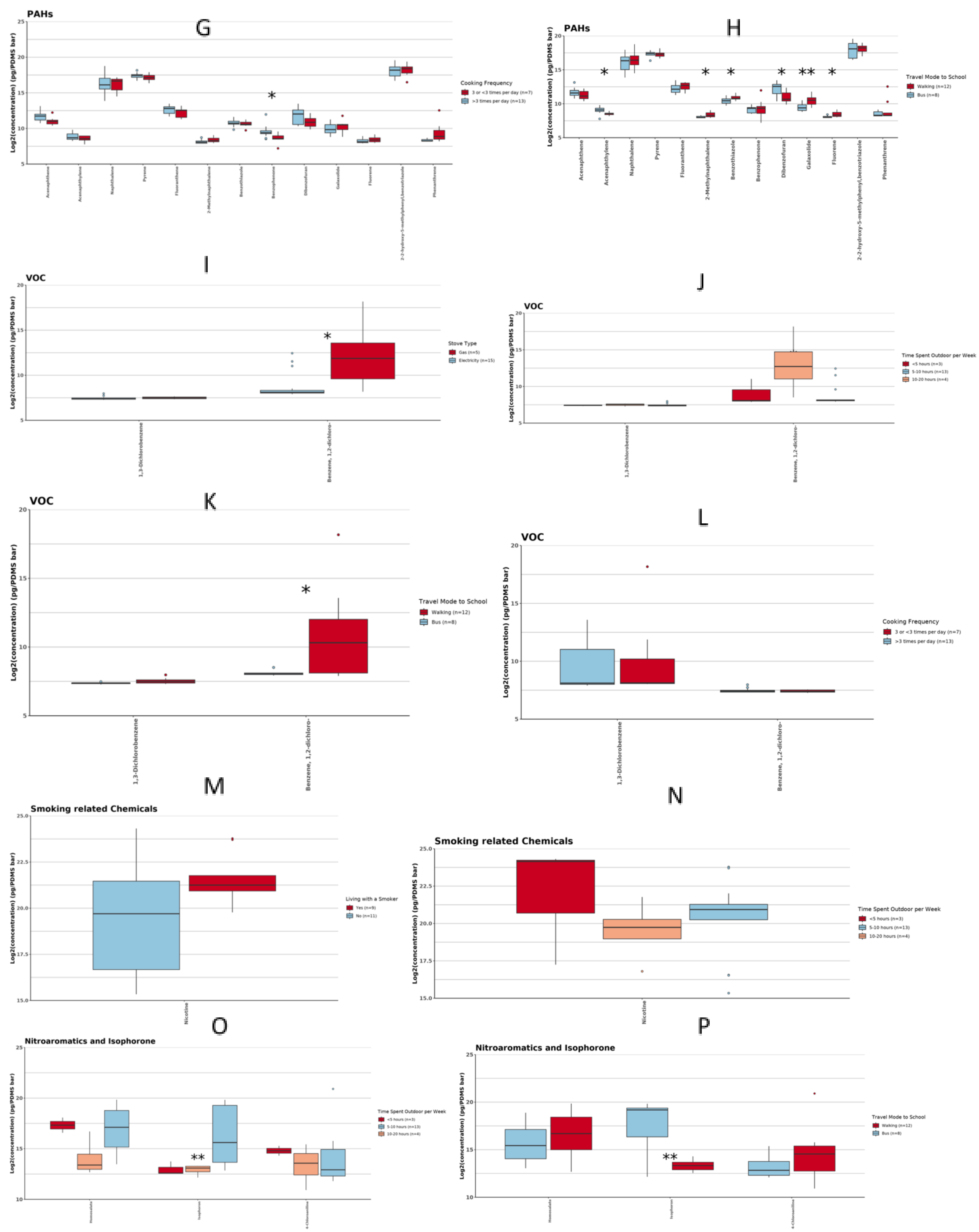
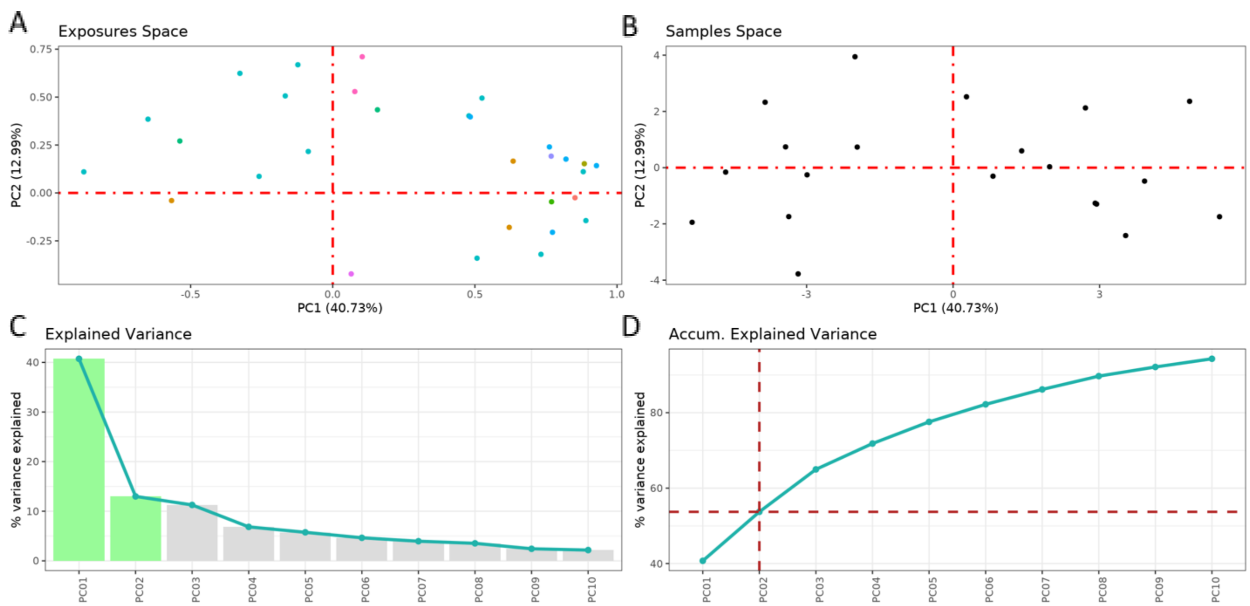


Figure 6. Chemical exposures of children by behavioral characteristics.

The correlations between principal component (PC) and behavioral characteristics of the study participants and different chemicals were used to demonstrate variance of chemical compounds were determined by which variables (Figure 7). There was no obvious clustering in either the chemical exposures or across the study participants (Figure 7 A&B). The top two PCs accounted for 53.72% of variance across exposure compounds (Figure 7C). For the cumulative proportion, PC1 explained around 40.73% of the total variance, which implied that almost half of the data in the set of 10 variables can be represented by the first principal component (Figure 7D). The first five principal components can explain 77.57% of the total variance. The correlations between PCs and chemicals were shown by the standardized loadings, demonstrating strong positive correlations between PC1 and PAHs such as galaxolide, 2-methylnaphthalene and 2-2-hydroxy-5-methylphenyl, benzotriazole, as well as strong negative correlation between PC1 and nicotine (Figure 7E). PC2 was correlated positively with dibenzofuran, diethyl phthalate and 1,2-dichlorobenzene, while PC3 was highly correlated with naphthalene, 2-chloro and PC7 was highly correlated with fluoranthene. Significant correlations seemed to be found between PC1 scores and several behavior characteristics such as household size, household income level, parent employment status, whether there is smoker at home and smoking frequency, whether bedroom window is facing a main traffic road and travel mode to school, while PC2 scores were significantly correlated with parents education level, household income level and behavioral factors such as cooking frequency and how often ventilation is used (Figure 7F). Moreover, stove type, how often ventilation used and travel time to school were associated with PC3.



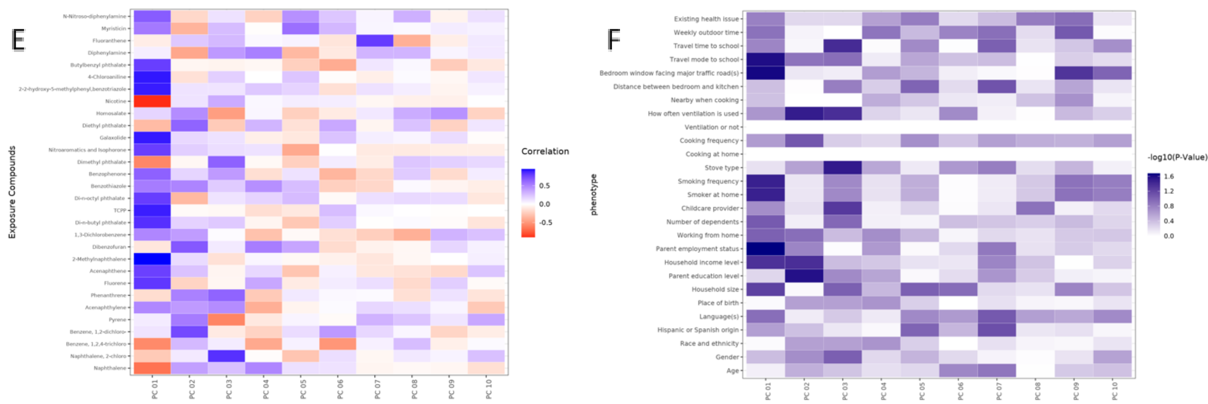
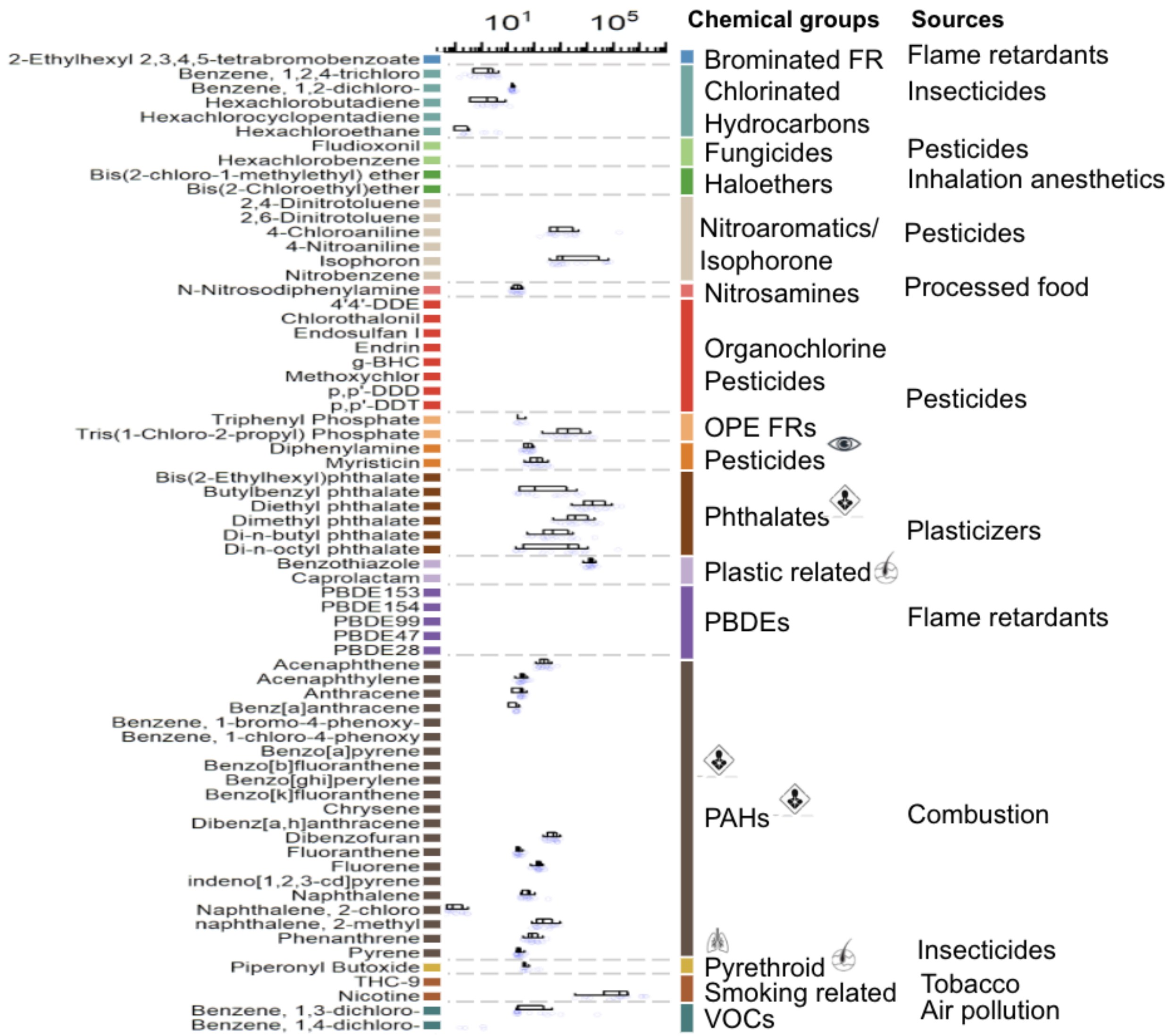


Figure 7. **Principal component analysis (PCA) of individual level of chemical exposure of study participants**. A) PCA in the exposures. B) PCA across the study participants. C) PC1 and PC2 accounted for around 50% of variance across exposure chemical compounds overall. D) Cumulative variability explained at each PC (vertical dashed line indicating the last PC and horizontal dashed line indicating the amount of explained variability). E) PC1 had the highest loading among the PAHs and PC2 had the highest loadings in dibenzofuran, diethyl phthalate and 1,2-dichlorobenzene. F) The associations between the phenotypes and PCs.

Discussion

Exposure Patterns and Potential Exposure Sources

This study presents individual levels of chemical exposures to an exhaustive mixture of indoor and outdoor contaminants of children in a low-income neighborhood in a developed country. The data collected by the Fresh Air wristbands, a novel wearable air sampler, suggest the participants were exposed to mainly phthalates (n=5) and PAHs (n=12), from a variety of sources such as plasticizers and combustion (Figure 8). The toxicity of detected chemicals were categorized into inhalation toxicity, ocular irritation, dermal toxicity and carcinogenicity using the prototype EPA Hazard Comparison Dashboard (EPA-HCD) (Vegosen and Martin, 2020).



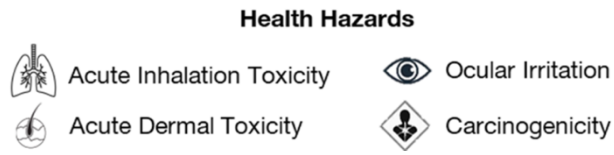


Figure 8. Chemicals of potential concerns.

According to the EPA-HCD toxicity characterization, study participants were exposed to chemicals of health concerns (Figure 8). They were exposed to several carcinogenic chemical compounds such as PAHs (naphthalene) from combustion and tobacco, phthalates (diethyl phthalate) from plastics and personal care products. Chemicals detected that have a high acute dermal toxicity included pyrethroid (piperonyl butoxide) from insecticides and benzothiazole from plastics. Diphenylamine from pesticides is associated with ocular irritation and pyrene from PAHs can result in acute inhalation toxicity. Carcinogenic chemical compounds and inhalation toxicity were of particular concern in the study, as they were detected to be prevalent across the participants and pose health threats.

Fresh Air wristbands have been deployed in other settings both in and outside of the United States (Guo et al., 2021; Koelmel et al., 2021a, 2021c; Lin et al., 2020). Unlike the cohort 1 study in MA, the distribution of detected chemicals in this Dwight neighborhood study (cohort 2) resembles with the cohort 3 in South Africa (Figure 9). In cohort 1, PAHs and PBDEs were the most prevalent chemical compounds detected, while for cohort 2 and 3, PAHs and phthalates were the most detected. Cooking activities in huts and limited ventilation were considered as the primary reasons for PAHs and phthalates exposure in cohort 3 and researchers also found a positive association between poverty level and certain combustion chemical exposures such as benzo(k)fluoranthene (Koelmel et al., 2021a). Study participants in cohort 2, though from a developed country, were also mainly from low-income households and there is a possibility that poverty plays a role in toxic chemical exposure. However, how poverty affects the level of toxic chemical exposure remains unknown. Apart from cooking activities and poor ventilation, PAHs are also found to be associated with road or street dust, and particulate matter in air pollution (Ali et al., 2021). Exposure to air pollution and dust is probably associated with elevated concentrations of PAHs detected in cohort 2. Although both cohort 1 and 2 studies were conducted in the United States, the chemical exposures varied greatly. Therefore, there is an emerging need for local studies.

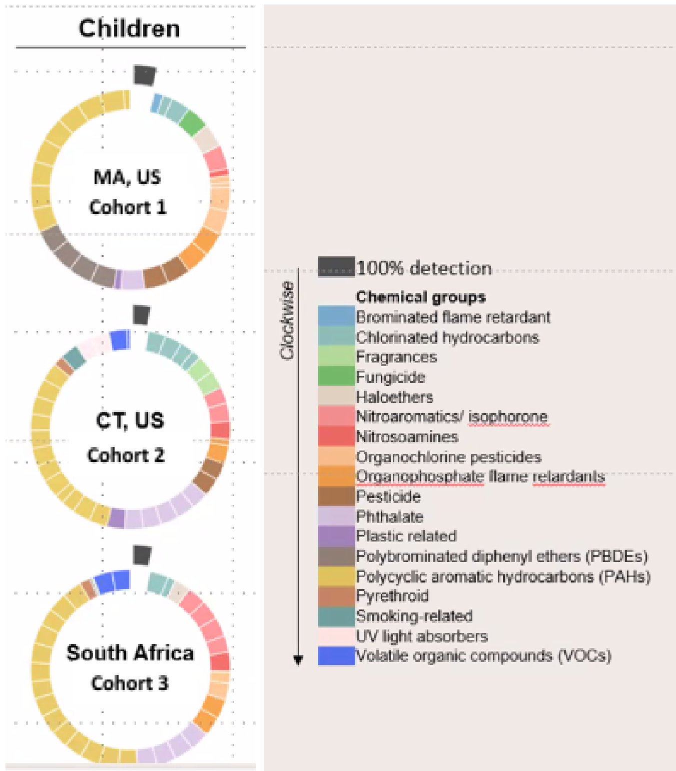


Figure 9. Comparison between detected chemicals using Fresh Air wristbands across different cohorts. Cohort 1: Springfield, MA children cohort (Lin et al., 2020); Cohort 2: New Haven, CT children cohort; Cohort 3: South African children cohort (Koelmel et al., 2021a).

In general, chemical exposure disparity across participants was not statistically significant based on gender, race/ethnicity or other characteristics. However, for certain classes of chemicals, exposure disparity across gender or race/ethnicity was indicated. For instance, female children were found to be exposed to more PAHs such as naphthalene and pyrene compared to male children (Figure 4). Black or African American children were exposed to more phthalates such as dimethyl phthalate, diethyl phthalate and butylbenzyl phthalate compared to non-Black children (Figure 5). However, due to limited sample size, this disparity could not be concluded with great confidence.

PAHs

This study evaluated 8 of the 16 RPA priority PAHs. Acenaphthene, dibenzofuran, fluorene, naphthalene and pyrene were detected in high concentrations. PAHs are known to be carcinogenic such as naphthalene, anthracene and benzo(a)pyrene, and high genotoxic such as anthracene, pyrene and fluorene. According to the International Agency for Research on Cancer (IARC), naphthalene is classified in Group 2, considered as possibly carcinogenic to humans. Naphthalene as a ubiquitous pollutant is associated with elevated cancer risk (Batterman et al., 2012; Griego et al., 2008; Jeffrey Lewis, 2012; North et al., 2008). Moreover, long-term exposure of low-dose PAHs such as pyrene was considered associated with skin and bladder cancer in laboratory animals (Armstrong et al., 2004; Diggs et al., 2012). Apart from carcinogenicity, PAHs also have adverse health outcomes in the respiratory system such as airways inflammation and deterioration of lung functions (Rodríguez-Aguilar et al., 2019; World Health Organization. Regional Office for Europe, 2010). Pyrene is associated with a high level of acute inhalation toxicity. In addition, naphthalene and anthracene can lead to skin irritation and redness, while high doses of exposure can cause the dissolve red blood cells (Rengarajan et al., 2015). Other adverse health effects associated with PAHs exposure includes damage to DNA, liver, kidney, human immune and reproductive system (John et al., 2009; Kim et al., 2013; Srogi, 2007).

Several PAHs chemicals are strongly correlated to each other (Figure 3). Pyrene and fluoranthene, pyrene and phenanthrene, fluoranthene and phenanthrene, fluoranthene and fluorene are all strongly positively correlated to each other, while pyrene and 2-methylnaphthalene, phenanthrene and 2-methylnaphthalene, fluoranthene and 2-methylnaphthalene are strongly negatively correlated to each other. However, due to lack of information, the causes behind this correlation pattern remain unknown and more research is warranted.

Phthalates

Despite PAHs, study participants were found to be exposed to high levels of phthalates. Five phthalates were detected by the wristbands: butylbenzyl phthalate, diethyl phthalate, dimethyl phthalate, di-n-butyl phthalate and di-n-octyl phthalate, usually used as plasticizers. The elevated concentrations of phthalates detected in the Dwight neighborhood are coherent with the phthalates concentration levels detected in different populations across the world (Bergmann et al., 2017; Blanchard et al., 2014; Bu et al., 2016; Chen et al., 2018; Dixon et al., 2019; Guo et al., 2021; Lunderberg et al., 2019). Although phthalates are widely applied in consumer products, food processing and medical industry and a growing interest in inhalation exposure, majority of the toxicological and epidemiological studies are focused on exposures through food or consumer products (Grosse et al., 2011; Kim et al., 2020; Romero-Franco et al., 2011; Wang et al., 2017). Moreover, high doses of phthalates on children are associated with allergic diseases, asthma and chronic illnesses (Bornehag and Nanberg, 2010; Braun et al., 2013). Diethyl phthalate was found to be associated with increased autistic-like behavior and increased BMI in children (Engel et al., 2010; Hatch et al., 2008; Miodovnik et al., 2011; Teitelbaum et al., 2012). Butylbenzyl phthalate exposure was correlated with elevated risks of allergic diseases such as asthma, rhinitis and eczema (Hsu et al., 2012; Just et al., 2012b, 2012a). From these long-term adverse health effects on children, high levels of phthalates detected in the Dwight study participants are concerning.

Indoor phthalate exposure remains a major health threat, especially to children. Despite consumer products, food packaging materials and medical devices that are commonly present in the indoor environment, phthalates are also widely applied in building materials. High molecular-weight phthalates such as butylbenzyl phthalate are often added to polymer plastics while the low molecular-weight phthalates such as dimethyl phthalate, diethyl phthalate and di-n-butyl phthalate are usually used in cosmetic and personal care products as well as surface coating materials (Bu et al., 2016; Kang et al., 2012). Phthalates are semi-volatile organic compounds (SVOCs) in the environment and can be absorbed on particulate matters and surfaces easily because of their low vapor pressure (Weschler and Nazaroff, 2010). Therefore, phthalates are almost ubiquitous in indoor environments. In the past two decades, there has been increasing public attention on the negative health impacts of phthalates exposures on children, leading to the US Consumer Product and Safety Improvement Act (CPSIA) in 2008, which banned using butylbenzyl phthalate and di-butyl phthalate in children's toys and childcare products (Ahmad et al., 2017). However, phthalates were found to be at high concentrations at childcare facilities in California (Gaspar et al., 2014). Similar levels of exposures were discovered in a variety of playrooms, daycare centers, indoor-playgrounds and kindergartens in South Korea (Kim et al., 2011). In China, where there are only few regulations on limiting phthalates exposure, phthalates concentrations were found to be higher in schools compared to offices, leading to higher exposures of children than adults (Liu et al., 2022).

To reduce phthalate exposures, healthcare providers suggested processed food, plastic food packaging, consumer products such as colognes and perfumes, cleaning/mopping windowsills and floors frequently (Braun et al., 2013).

Other airborne chemical exposure

Personal exposure to flame retardants and pesticides was detected at very low concentrations and no polybrominated diphenyl ethers (PBDEs) and organochlorine pesticides were detected for the Dwight study participants. The observed level is consistent with the development of alternatives for PBDEs in 2004 due to their toxicity in endocrine disruption and bioaccumulation and the phase-out of organochlorine pesticides in developed countries in 1970s due to their toxicity and carcinogenicity (Dodson et al., 2012; Karasali and Maragou, 2016; US Department of Commerce, 2023). The low concentrations of other pesticides and insecticides such as chlorinated hydrocarbons detected reflects the urban environment of the study location.

Apart from the non-detected PBDEs, other flame retardants organophosphate Ester (OPE) were detected at a relatively high concentration. This aligns with the fact that OPE has been developed to be the alternative of PBDEs (Blum et al., 2019). Despite being used as flame retardants, OPE are also commonly found in plasticizers in consumer products and construction materials (Mendelsohn et al., 2016). Compared to PBDEs that have long half-lives and can stay in human bodies from weeks to years, OPE can be metabolized very quickly in hours or days (Geyer et al., 2004; Hoffman et al., 2014). Although there is a wide application of OPE flame retardants, their toxicity and human health effects are not well-studied or well-understood. Epidemiological evidence suggests OPE is associated with adverse effects on the reproduction system such as reduced rate of fertilization, adverse health outcomes on children development such as poor memory and decreased IQ (Carignan et al., 2018; Hoffman et al., 2017). Whether OPE is a "good" substitution for PBDEs remains a question and policy makers should respond to concerns and inform consumers with available information to protect the vulnerable population such as children.

Certain chemicals are particularly harmful to children's health e.g. VOCs, nitroaromatics, isophorone and pyrene. Isophorone and 4-chloroaniline were detected at relatively high levels, which have high carcinogenicity and genotoxicity mutagenicity as well as cause skin and eye irritation. VOCs such as 1,3-dichlorobenzene have high toxicity in endocrine disruption. The chemical of the highest detection in the study – homosalate, commonly found in personal care products and cosmetics such as sunscreen, is a potential endocrine disruptor. The European Commission has restricted the use of homosalate in personal care products after the Scientific Committee on Consumer Safety (SCCS) Scientific Advice 1638/21 of December 2021 (S, 2022). However, skincare products with homosalate are still prevalent in the US, which explains the level of exposure observed in the study. Even though not all chemicals were detected at high levels in the study population, minimum exposure levels, especially in the long-term, can already pose a threat to children's health.

In this targeted analysis, Fresh Air wristbands measured 70 compounds and 30 of them were detected at abundance for assessment, spanning 10 chemical classes. The targeted list of chemicals reflects only a small number of airborne contaminants compared to chemicals that people are exposed to in daily life. Therefore, additionally we will conduct a suspect screening and non-targeted analysis of the wristband data collected from the Dwight children. We hope the results can further inform local communities and policy makers for understanding unexpected or unknown environmental chemical exposures.

Strengths and Limitations

This study provides baseline data for chemical exposure of understudied population i.e. racial minority children from low-income families in a developed country. Compared to traditional stationary air monitors, wearable air samplers can measure air pollution and chemicals exposed at the individual level and can let researchers determine health impacts due to exposure more accurately. Previously wearable air samplers are high-cost, heavy-weighted and sometimes invasive (e.g. noises, tubes). Fresh Air wristbands are low-cost, light-weighted and passive air samplers, which can be easily worn by vulnerable populations such as children and seniors. The wristbands can potentially be deployed to a large population for more comprehensive studies. This Dwight study also indicates potential association between chemical exposures and household characteristics or daily activity patterns. Exposure disparity across gender and race/ethnicity was also addressed.

However, there are also limitations in the study. The major limitation of the study is the small sample size, which makes the results difficult to be generalizable to other populations. Also due to the sample size consideration, this study compared Black and non-Black children and this result may have skewed the differences among the non-Black races, as children were of various race/ethnicity in the study e.g. White, Hispanic/Latinx, Asian. A detailed determination of exposure disparity across race/ethnicity requires more research. Moreover, more research is needed for larger sample sizes, different chemicals, other locations and so on. Lastly, compliance issues possibly due to the young age of study participants resulted in the low return rate of the air samplers, which hindered the analysis.

Conclusion

Fresh Air wristbands, affordable and wearable air samplers, were used to determine the individual level of chemical exposure of children living in the Dwight neighborhood in New Haven, CT. The 30 detected chemicals were discovered to be mainly PAHs and phthalates, differing from the exposure patterns based on other US locations using the same type of wristbands. The data collected can potentially fill in the gap between individuals' daily activities and the observed personal exposure level. This study provides baseline data for low-income and predominantly racial minorities communities in a developed country, and further chemical analysis can be conducted through suspect screening and non-targeted analysis. However, due to limited sample size, the results may not be generalizable and more research with larger sample sizes is needed to understand chemical exposure of vulnerable communities and the adverse health outcomes.

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