

Consumer behavior and exposure to parabens, bisphenols, triclosan, dichlorophenols, and benzophenone-3: Results from a crowdsourced biomonitoring study

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ABSTRACT

Nearly all Americans have detectable concentrations of endocrine disrupting chemicals from consumer products in their bodies, and expert panels recommend reducing exposures. To inform exposure reduction, we investigated whether consumers who are trying to avoid certain chemicals in consumer products have lower exposures than those who are not. We also aimed to make exposure biomonitoring more widely available. We enrolled 726 participants in a crowdsourced biomonitoring study. We targeted phenolic compounds—specifically parabens, bisphenol A (BPA) and analogs bisphenol F (BPF) and bisphenol S (BPS), the UV filter benzophenone-3, the antimicrobial triclosan, 2,4-dichlorophenol, and 2,5-dichlorophenol—and collected survey data on consumer products, cleaning habits, and efforts to avoid related chemicals. We investigated associations between 68 self-reported exposure behaviors and urine concentrations of ten chemicals, and evaluated whether associations were modified by intention to avoid exposures. A large majority (87%) of participants reported taking steps to limit exposure to specific chemicals, and, overall, participants achieved lower concentrations than the general U.S. population for parabens, BPA, triclosan, and benzophenone-3 but not BPF and BPS. Participants who reported avoiding all four ingredient groups—parabens, triclosan, bisphenols, and fragrances—were twice as likely as others to be in the lowest quartile of cumulative exposure. Avoiding certain products and reading ingredient labels to avoid chemicals was most effective for parabens, triclosan, and benzophenone-3. Avoiding BPA was not effective for reducing bisphenol exposures. Avoiding certain chemicals in products was generally associated with reduced exposure for chemicals listed on labels. Greater ingredient transparency will help consumers who read labels to reduce their exposure to a wider range of potentially harmful chemicals. In order to more equitably address public health, labeling policies should be complemented by regulations that exclude harmful chemicals from consumer products.

1. Introduction

Many common consumer product ingredients have been identified as endocrine disrupting chemicals (EDCs) because they affect hormone signaling (Dodson et al., 2012), and nearly all Americans have detectable concentrations of these chemicals in their bodies (CDC, 2019). Based on evidence of diverse health effects, expert panels and medical societies have recommended reducing exposures (American College of

Obstetricians and Gynecologists, 2013; Gore et al., 2015).

Individual-level strategies to reduce exposures include avoiding products that are likely to contain the ingredients of concern, choosing products based on ingredient labels, or shopping with retailers that screen products to exclude the chemicals. Evidence showing associations between use of certain consumer products and urine concentrations of parabens and other phenols supports the hypothesis that avoiding products will reduce exposure (Ashrap et al., 2018; Berger

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et al., 2019; Braun et al., 2014; Ferguson et al., 2017; Meeker et al., 2013; Nassan et al., 2017; Philippat et al., 2015). For example, more frequent use of personal care products and specifically lotions, sunscreen, cosmetics, some hair products, nail polish, and mouthwash was associated with higher urinary concentrations of parabens (Ashrap et al., 2018; Berger et al., 2019; Braun et al., 2014; Ferguson et al., 2017; Meeker et al., 2013; Nassan et al., 2017; Philippat et al., 2015). Use of sunscreen, lotions, shaving cream, and cosmetics was associated with higher urinary concentrations of the UV filter benzophenone-3 (Ashrap et al., 2018; Ferguson et al., 2017; Meeker et al., 2013; Philippat et al., 2015). Liquid soaps and toothpaste, specifically Colgate Total® toothpaste, have been associated with higher triclosan concentrations (Ashrap et al., 2018; Berger et al., 2019; Meeker et al., 2013).

In addition, intervention studies have successfully reduced exposure to bisphenol A (BPA), parabens, and benzophenone-3, which have short biological half-lives, making them good candidates for intervention studies. Consuming fresh foods rather than canned food or food stored in plastics led to an over 50% reduction in urinary BPA concentrations (Rudel et al., 2011). Urinary concentrations of methyl and propyl paraben and benzophenone-3 decreased significantly in Latina teens who were provided with alternative personal care products (Harley et al., 2016).

In these successful intervention studies, researchers supplied alternative food or products to participants, leaving open the question of whether the results can be generalized to a broader population of consumers selecting products on their own. We had a unique opportunity to investigate this question in a self-selected population of volunteers in a crowdsourced biomonitoring study, Detox Me Action Kit (DMAK). Crowdsourcing is an online participatory activity in which people voluntarily and jointly undertake a task, variously contributing—for

example, their time, money, biological samples, data, or expertise—for mutual benefit (Estellés-Arolas and González-Ladrón-de-Guevara, 2012). In this study, participants benefited from learning their own results together with personalized information about exposure reduction, and they contributed to new knowledge that is scientifically useful about the sources of chemical exposures. We hypothesized that this crowdsourced population would include a group of consumers who were actively trying—outside of any guided intervention study—to reduce their exposure to EDCs in consumer products. We investigated associations between self-reported exposure behaviors and urine concentrations of certain EDCs that are common in consumer products, including some ingredients that are more readily avoidable and some that are not. We hypothesized that people who are avoiding certain products or ingredients would have lower exposure. We chose to measure exposures to a set of phenolic compounds that are commonly used in consumer products and are known to mimic estrogen or have other hormone activity: parabens, benzophenone-3, triclosan, bisphenols (e.g., BPA), and dichlorophenols. Common sources, toxicity information, and labeling requirements for these chemicals are shown in Table 1.

2. Methods

2.1. Study population

We collected samples from 726 U.S. participants through an online crowdsourced platform, Detox Me Action Kit, launched in December 2016 (Silent Spring Institute, 2019). To recruit participants, we used social media and emailed newsletters to the networks of Silent Spring Institute and of other breast cancer and environmental organizations. News media coverage brought additional attention to the study,

Table 1
Common sources, associated toxicity, and labeling requirements for phenolic chemicals measured in this study.

Chemical(s)	Sources	Toxicity	Labeling Requirements
parabens	Preservatives in personal care products (Dodson et al., 2012; Guo and Kannan, 2013; Helm et al., 2018); used as food additives, in pharmaceuticals, and in other consumer products such as pesticides, paints, and toys (Dionisio et al., 2015; Goldsmith et al., 2014)	Weakly estrogenic in vitro and associated with altered hormone signaling in women (Aker et al., 2018)	Listed as ingredients on cosmetics to meet FDA labeling requirements (Dodson et al., 2012; Food and Drug Administration, 1938, 1967).
benzophenone-3	Ultra-violet (UV) filter used as an active ingredient in sunscreens and personal care products (Dodson et al., 2012) and is also added to plastics and other materials to protect the material and the contents from UV (Suzuki et al., 2005).	Estrogenic in vitro and in vivo (Kunz and Fent, 2006; Schlumpf et al., 2004)	Must be listed on cosmetics and on product labels when used as an active ingredient (Dodson et al., 2012; Food and Drug Administration, 1938, 1967). Does not have to be listed for other uses.
bisphenols (BPA, BPF, BPS)	Found in polycarbonate plastics and epoxy resins, some of which are used in can linings (Lehmler et al., 2018). BPF may be found in mustards (Zoller et al., 2016). BPS may also be found in thermal paper, including receipts, and food contact materials (Liao et al., 2012; Ndaw et al., 2018; Thayer et al., 2016).	Associated with effects on the developing brain, reproductive tract, and breast (Chen et al., 2016; Pelch et al., 2019).	Few labeling requirements for many products that may contain BPA and its analogs. Some products marketed as “BPA free.”
triclosan	Used in some antibacterial hand soaps until the US Food and Drug Administration ban (Food and Drug Administration, 2016), and it may still be found in other personal care products like toothpaste and deodorant (Dodson et al., 2012). Also used in household goods and medical devices (Halden, 2014).	Associated with a dose-dependent decrease in thyroid hormones in rats (Crofton et al., 2007; Paul et al., 2010; Rodriguez and Sanchez, 2010); weakly estrogenic (Halden et al., 2017); allergic sensitization (Spanier et al., 2014).	Must be listed on cosmetics and on product labels when used as an active ingredient (Dodson et al., 2012; Food and Drug Administration, 1938, 1967). Does not need to be labeled for other uses.
2,4-dichlorophenol	Minor degradation product of triclosan and is also a metabolite of 2,4-D, an herbicide (Canosa et al., 2005; Ye et al., 2014). Drinking water contaminant (National Center for Biotechnology Information, 2020a).	Immunotoxicity (Exon et al., 1984; U.S. EPA, 1987)	When used as a pesticide, the parent chemical 2,4-D needs to be labeled; however, no labeling requirements in other applications (Environmental Protection Agency, 1972).
2,5-dichlorophenol	Metabolite of 1,4-dichlorobenzene, a disinfectant and pesticide used in mothballs and deodorizers, and may have other uses (California Office of Environmental Health Hazard Assessment, 2020; NTP, 2016; Ye et al., 2014; Yoshida et al., 2002). Drinking water contaminant (National Center for Biotechnology Information, 2020b).	Parent compound 1,4-dichlorobenzene is carcinogenic (California Office of Environmental Health Hazard Assessment, 2020; NTP, 2016)	When used as a pesticide, parent chemical 1,4-dichlorobenzene needs to be labeled; however, no labeling requirements in other applications (Environmental Protection Agency, 1972).

including an article in *The New York Times* (Kristof, 2018). Most participants enrolled after contributing to the study (originally \$299 for an individual kit); others enrolled after contributions by family or friends, or were supported by other charitable contributions to the project. Payment information was kept separate from information about participants (*i.e.*, study personnel did not know who paid for the kits). Samples were collected between February 2017 and October 2018. Adults could enroll throughout the study and children (zero to 17 years old) could enroll starting in March 2017. Detox Me Action Kit was first hosted for 30 days on [Indiegogo.com](#) and then on the Silent Spring Institute website. Participants provided informed consent separately to have their urine sample analyzed, to allow their sample to be stored for future chemical analysis, to allow de-identified data to be shared with other researchers, to be contacted with additional questions, and to receive their results. The study was approved by Hummingbird IRB (IORG0007741, Needham, MA).

2.2. Questionnaire and *a priori* hypotheses

Participants were asked to complete an online survey after collecting their morning urine sample. Questions included demographics, product use within the last 24 h and last year, and whether they avoided certain chemicals when purchasing products. Specifically, we asked participants if they avoided products with “parabens,” “BPA or bisphenol A,” “triclosan or products that are described as antibacterial or antimicrobial,” and “fragrance” on the label. We asked about avoiding fragrance but did not measure any fragrance chemicals in urine. If participants reported using certain products that likely contained a chemical of interest, we asked them to examine the product and tell us whether the ingredient list included the chemical. Ingredient reading was only done for products that likely contain parabens, benzophenone-3, or triclosan, since our earlier research indicated that these chemicals are often on the product labels (Dodson et al., 2012). Survey questions are available from the authors. Prior to data analysis, we created a list of products and other exposure behaviors that we considered likely sources of exposure for each chemical class. For a list of *a priori* predictors, see Table S1 in Supplementary Material.

2.3. Urine sample collection

Urine collection kits were mailed to participants. Kits included an insulated shipping box containing two 4oz amber glass jars (Environmental Sampling Supply), instructions, an overnight shipping label, ice packs, and shipping materials (materials available from authors upon request). Participants were instructed to collect two urine samples—one in the evening and the first void the following morning—and to freeze the samples and ice packs in their home freezer for at least 24 h before mailing them back via overnight mail. We collected evening and morning samples to represent a day’s exposure for these rapidly metabolized compounds, without burdening participants with a full 24 h collection. Samples were inspected at Silent Spring Institute and frozen at -20 °C.

2.4. Sample analysis

Frozen samples were shipped overnight on blue ice to the analytical laboratory. The first 295 samples were analyzed at NSF International (Ann Arbor, MI USA), the second 354 samples were analyzed at SGS AXYS Analytical (Sidney, BC Canada), and the last 77 samples at NSF International. We switched between laboratories to accommodate their availability. Samples were thawed at the laboratory, and the two urine samples were composited in equal volumes to yield a single composite for each participant.

We targeted 10 analytes: methyl paraben, ethyl paraben, propyl paraben, benzophenone-3, BPA, BPF, BPS, triclosan, 2,4-dichlorophenol, and 2,5-dichlorophenol. Target analytes were measured using

solid-phase extraction (SPE) coupled to high-performance liquid chromatography-isotope dilution tandem mass spectrometry (HPLC-MS/MS), operated in negative mode. Briefly, the conjugated species of the target analytes in urine were hydrolyzed by use of beta-glucuronidase/sulfatase. After hydrolysis, analytes were pre-concentrated by SPE, separated by reversed-phase HPLC and detected by a mass spectrometer operating in negative ionization and multiple reaction monitoring (MRM) mode. Analyte recovery was verified on a sample-to-sample basis using isotopically-labeled surrogate standards. Method performance results and reporting limit of quantification can be found in the Supplementary Material.

2.5. Quality assurance/quality control

We implemented several quality control measures to assess the accuracy and reliability of our data (Udesky et al., 2019). Detailed information on QA/QC data and procedures is provided in Supplementary Material and summarized here. Potential contamination from the laboratory was assessed with blank samples (see Supplementary Material). The method reporting limit (MRL), defined as the maximum of the analytical detection limit (for SGS AXYS lab this was sample-specific) and the 90th percentile of all blanks (reagent blanks and shipment blanks), represents the level above which we are confident in the reported result (see Tables S2-S4). If a chemical was consistently detected at low levels across a large number of blanks, we considered this evidence of potential systematic bias and blank-corrected data by subtracting the median value detected in blanks (see Table 2 and Tables S3-S4). When available (values from NSF) we included estimated values below the analytical detection limit when deciding whether to perform blank-correction. Accuracy was assessed using laboratory control spiked samples. Because SGS AXYS did not include a matching isotope-labeled surrogate for BPF, we only report BPF results from NSF. We used split samples to quantify precision.

2.6. Study results reporting

We provided personal results reports to participants who consented to receive them. Participants used unique passcodes to access their report online via the Digital Exposure Report-Back Interface (DERBI) (Boronow et al., 2017). We mailed paper reports to participants who requested them. Each report summarized an individual’s results relative to other study participants and national concentrations from the National Health and Nutrition Examination Survey (NHANES). Reports included an overview of study findings, what is known about health effects, strategies for reducing exposure, and contact information to speak with a researcher. An example report is shown at [dmakdemo.com/report](#).

2.7. Data analysis

The two analytical laboratories reported results using slightly different approaches. NSF reported values as detected, estimated, or not detected, and provided one detection limit for each analyte. SGS AXYS reported values as detected or not detected, and provided sample-specific detection limits for each sample and analyte. Thus, data are multiply left-censored (*i.e.*, there are multiple detection limits for each chemical). One laboratory (NSF) reported values less than or equal to zero, which can occur when there is a peak on the chromatogram (indicating the presence of a target chemical) and extrapolation beyond the lower limit of the calibration curve. When this occurred ($n = 35$), we treated the values as censored. We did not adjust for creatinine because samples were composited.

To account for multiply left-censored data, we used the nonparametric Kaplan-Meier method from the NADA package (Lee, 2017) to estimate means, standard deviations, and medians. The Kaplan-Meier method, originally developed for survival analysis (right-censored

Table 2

Summary statistics of urine concentrations (ng/ml) measured in DMAK participants.

Chemical	Abbrev.	N ^a	MRL ^b	% > MRL ^c	Kaplan-Meier ^d			Range ^e	95th percentile	99th percentile
					mean	std. dev.	median			
<i>Parabens</i>										
methyl paraben ^g	MePB	726	0.77	100	65.9	216	12.3	0.566–3640	267	666
ethyl paraben	EtPB	726	1	79	9.53	37.4	1.37	0.141–744	38	114
propyl paraben	PrPB	726	0.2	91	15.2	59.7	1.33	0.077–1000	60	264
<i>UV filters</i>										
benzophenone-3 ^g	BP3	726	0.28	100	154	568	21.7	0.365–8160	708	2350
<i>Antimicrobials</i>										
triclosan ^g	TCS	726	1.8	37	28.7	180	0.630	0.655–3680	124	491
<i>Bisphenols</i>										
bisphenol A ^g	BPA	726	0.28	75	2.57	25.2	0.62	0.203–624	4.09	15.7
bisphenol F ^g	BPF	372 ^f	0.24	90	2.33	8.59	0.841	0.241–117	5.89	29.1
bisphenol S ^g	BPS	726	0.28	81	2.32	34.2	0.48	0.084–921	3.36	11.4
<i>chlorinated phenols</i>										
2,4-dichlorophenol ^{g,h}	DCP24	726	0.1	52	0.582	1.11	0.235	0.108–9.75	2.98	7.06
2,5-dichlorophenol	DCP25	726	0.2	55	4.83	18.4	0.81	0.210–242	22.4	95.8

^a number of samples varies by analytical laboratory. A total of 726 samples were analyzed by two different laboratories.^b median method reporting limit (MRL).^c percent of samples above sample-specific MRL, includes two BPA samples and one 4tOP sample flagged as “estimated maximum” concentration.^d non-parametric descriptive statistics method for left-censored data. Estimated values (values below MRL and reported by the laboratory) used in calculating statistics. Values shown only if at least 35% of values reported by the lab.^e Range of detected (above MRL) concentrations.^f BPF results from SGS AXYS not reported due to quality assurance/quality control issues.^g values from NSF (N = 372) subject to blank correction by subtracting median blank value.^h two non-detect values dropped from Kaplan-Meier statistics because they exceeded the maximum uncensored value.

data) and adapted for use with left-censored data, is recommended for data sets with <50% censoring (Helsel, 2005). We included estimated values below the MRL in these calculations but not in subsequent analyses. We estimated correlation among analytes using nonparametric Kendall's tau beta adjusting for left-censoring and with p-values obtained from 10,000 bootstrap replications (Newton and Riedel, 2007). Statistical tests with p-values < 0.05 were considered significant.

In subsequent analyses we used the molar sum of methyl, ethyl, and propyl paraben, because they were moderately correlated. We calculated the molar sum by dividing each metabolite concentration by its molecular weight and then summing: $\Sigma_{\text{parabens}} = [(\text{ethyl paraben}^*(1/166.17 \text{ g/mol}) + (\text{methyl paraben}^*(1/152.15 \text{ g/mol}) + (\text{propyl paraben}^*(1/180.2 \text{ g/mol}))]$.

We investigated associations between demographic variables (age, gender, race/ethnicity, education) and measured concentrations using multivariate regression models. Age was treated as a continuous variable, gender as binary (male vs. female), race/ethnicity as binary (non-Hispanic White vs. not non-Hispanic White), and education as binary (less than or equal to college degree vs. graduate degree). The response “prefer not to answer” was treated as missing data and dropped from analyses. We used censored regression (“cenreg” function, assuming a lognormal outcome distribution, in the NADA R package) since our data were left-censored.

2.7.1. Comparison to NHANES

We compared concentrations in our study with the NHANES 2015–2016 cycle, the most recent cycle available. NHANES data were compiled and summarized using the R package RNHANES (Susmann, 2016). To be consistent with how NHANES reports data, we substituted non-detects in our data set with the MRL/sqrt(2) for this comparison (CDC, 2019; Hornug and Reed, 1990). We visually compared the concentration distributions between this study and NHANES for adult (≥ 18 years old) Non-Hispanic White (NHW) female participants (the largest demographic group in this study).

2.7.2. Associations with product use

We evaluated the correlations among self-reported product use with

the phi statistic, a measure of association between two nominal variables. The larger the phi statistic, the more correlated the variables. For each chemical, we modeled associations one-by-one for each individual product (use in the previous 24 h) and also for variables that summed use of related products (e.g., any makeup) hypothesized *a priori* to be associated with the chemical. For less-frequent behaviors, such as cleaning and eating canned food, we used the yearly frequency data to create a binary indicator of at least regular use (1–5 times per week) or less than regular use.

For parabens and benzophenone-3, we considered overall product use, because we identified a large number of products that could be sources of these chemicals that are likely to be used simultaneously. Specifically, we evaluated associations between Σ_{parabens} and benzophenone-3 urine concentrations and total number of paraben or benzophenone-3-related products using a categorical variable for quartiles of number of products used. For Σ_{parabens} , we separately evaluated quartiles of product use for avoiders and non-avoiders. Many of our analyses distinguished between participants who reported avoiding certain chemicals when selecting products (“avoiders”) and those who did not report avoiding certain chemicals (“non-avoiders”). Participants could have different avoidance statuses for each of three chemical groups: parabens, bisphenols, and triclosan and its degradation product 2,4-dichlorophenol (Canosa et al., 2005). Using responses to the label-reading questions, we created a new variable ('any products with ingredients') indicating whether or not a participant used a product in the last 24 h that listed the chemical on the label. To evaluate whether people who are trying to avoid certain chemicals are less likely to use certain products, we compared the proportion of participants using a particular product among avoiders versus non-avoiders using a two-sample two-sided test of proportions. We compared the urine concentrations among three groups: (1) participants who did not use a product, (2) those who used the product and avoided the related chemical, and (3) those who used the product and did not avoid the chemical. We created a categorical variable representing these groups (nonuser, user + avoider, user + non-avoider) and used it in censored regression models (cenreg function in the NADA R package assuming a lognormal outcome distribution).

We then evaluated the association between product use and urine concentrations and whether that association was modified by avoidance status, again using censored regression. To account for the contribution from use of other products that might contain the chemical, we created weighted product counts that included all other products that are likely to contain the chemical of interest that the individual reported using except for the specific product use being modeled and included these counts in the regression models. Weighted product counts were calculated using mean product weights estimated from weighted quantile sum (WQS) regression ('gWQS' R package (Renzenzetti et al., 2019)). WQS simultaneously analyzes the impact of multiple products, represented by a personal care product use score, on measured urinary concentrations (Nassan et al., 2017). The product score is a composite score of products used from the linear combination of product use indicators (yes/no). We estimated mean product scores for each product from estimated product weights generated from 100 random trials (iterations) including 1000 bootstraps each (see Figure S1 in Supplementary Material). For parabens, bisphenols, triclosan, and 2,4-dichlorophenol, models included individual product use, weighted count of all other product use, avoidance status, and the interaction between individual product use and avoidance status. The interaction term evaluates whether avoidance status modifies the relationship between product use and urine concentration. In other words, we compared the association between product use and urine concentrations among those who avoid the chemical (avoiders) and among those who did not avoid the chemical (non-avoiders). We present the marginal effect estimates for avoiders and non-avoiders as percent difference in concentration for users compared to non-users. We included product use in the interaction models only when there were at least 5% of participants in each product by avoidance group. Our final models also included demographic covariates for gender, race/ethnicity, age, and education status. Models adjusted for other product use but not demographic covariates are presented in Supplementary Material. For 2,5-dichlorophenol and benzophenone-3, censored regression models included only product use, weighted product count for other products and demographics, because avoidance status was not available for these compounds.

Finally, we investigated if cumulative exposure differed by behavior. We calculated a cumulative exposure rank for each participant by ranking participants' urine concentrations for each chemical (setting non-detects to the MRL), summing the ranks, and then ranking the sums. We then compared behaviors among participants in each of the second to fourth quartiles to those in the lowest quartile using logistic regression.

Analyses were conducted in R version 3.6.0 (R Core Team, 2019).

3. Results

3.1. Participant characteristics

726 participants provided urine samples and 575 (79%) of them completed the survey. Most participants (65%) self-identified as female (Table 3). Eighty-four percent self-identified as non-Hispanic White, 2% as African-American or Black, 5% as Hispanic or Latino/a, 5% as Asian, 3% as Other, and 4% more than one race/ethnicity. Participants were between 2 and 94 years old at the time of urine collection (mean = 50; IQR = 39–64 years old). Most had a high level of education, with 25% holding a bachelor's degree and an additional 64% holding a graduate degree. Participants lived in 38 U.S. states, with the largest number from Massachusetts (30%), New York (15%), and California (14%). All but two participants consented to receive their results.

3.2. Urine concentrations

Measured urine concentrations spanned orders of magnitude for most chemicals (Table 2). For example, the maximum benzophenone-3 concentration was 20,000 times higher than the minimum and 300

Table 3

Participant Characteristics	n (%) ^a
Gender ^b	
Female	377 (65%)
Male	182 (32%)
Age	
≤18 years	29 (5%)
19–30 years	39 (7%)
31–50 years	184 (32%)
51–70 years	271 (47%)
>71 years	38 (7%)
Education	
≤ Bachelor's degree	185 (32%)
Graduate degree	368 (64%)
Race/Ethnicity	
Non-Hispanic White (NHW)	482 (84%)
Not NHW	52 (9%)

^a Missing data (no response) not presented.

^b Two participants reported being non-binary and not included in subsequent analyses involving binary gender categories.

times higher than the median. Methyl paraben and benzophenone-3 were found in 100% of participants and at the highest concentrations. Propyl and ethyl paraben concentrations were generally an order of magnitude lower than methyl paraben. The disinfectant triclosan was detected above the MRL in 37% of samples with another 44% estimated values below the MRL (the remaining 19% were non-detects). Chlorinated phenols 2,4-dichlorophenol and 2,5-dichlorophenol were detected at concentrations above the MRL in approximately 50% of samples, and 2,5-dichlorophenol concentrations were about 10x those of 2,4-dichlorophenol. While our detection limits (or MRLs) are comparable to NHANES for most of the chemicals, they were higher for both 2,4-dichlorophenol and 2,5-dichlorophenol. We found BPA (75% above MRL), BPF (90% above MRL), and BPS (81% above MRL) at similar concentrations (means of 2.6 ng/ml, 2.3 ng/ml, and 2.3 ng/ml, respectively).

Urine concentrations were moderately correlated for most chemicals, except BPS, which was not correlated with the parabens, triclosan, or BPF (Figure S2). Methyl and propyl paraben had the highest positive correlation (Kendall's tau beta = 0.57, p < 0.001), followed by 2,4-dichlorophenol and 2,5-dichlorophenol (Kendall's tau beta = 0.43, p < 0.001). Triclosan and 2,4-dichlorophenol, a degradation product of triclosan, were also correlated (Kendall's tau beta = 0.21, p < 0.001).

Concentrations of some chemicals differed by gender, age, race/ethnicity, and education (Table S7). Males tended to have lower benzophenone-3 and propyl paraben concentrations and higher triclosan and BPS. Paraben concentrations increased with age. Participants who were not Non-Hispanic White (NHW) had higher concentrations of the disinfectant metabolite 2,5-dichlorophenol.

We limited the comparison of DMAK participants with NHANES to white women, because 65% of DMAK participants are NHW women. Compared with NHW women in NHANES, NHW women in our study had a lower median urine concentration of methyl paraben, ethyl paraben, propyl paraben, benzophenone-3, triclosan, and BPA (Figure S3). The median for methyl paraben—a common preservative in cosmetics—was five times lower in DMAK compared to NHANES. On the other hand, DMAK participants had higher median concentrations of BPF and BPS compared with NHANES.

3.3. Self-reported product choices

Nearly all DMAK participants reported using toothpaste (96%) and hand soap (95%), and most used bar soap (84%) and dish liquid (82%) within the day before they collected their urine sample (Table S1). At

least half reported body lotion, face cream, face soap, deodorant, lip balm, shampoo, conditioner, drinking from a plastic water bottle, or eating prepared food. In contrast, few reported using moth balls (1%) or toilet bowl deodorizers (1%). Behaviors that we expected to be related were positively correlated (Figure S4); for example, participants who used mascara tended to use foundation ($\phi = 0.57$) and lipstick ($\phi = 0.48$).

3.4. Associations between product use, ingredient avoidance, and exposures

Most participants said they avoided at least one type of chemical in the study. Eighty two percent reported avoiding buying products with “BPA” or “bisphenol A” on the label, 65% avoided “parabens,” 65% avoided “triclosan” or products labeled as “antibacterial” or “antimicrobial,” and 65% avoided buying products with “fragrance” on the label. Forty one percent of participants reported avoiding all four chemical classes. Avoidance of one ingredient was correlated with avoidance of others (Figure S4).

3.4.1. Parabens

Using more products was associated with significantly higher paraben concentrations for both avoiders and non-avoiders of parabens, but the relationship was more pronounced among non-avoiders (Fig. 1). Among avoiders, being in the highest quartile of product use (more than 11 paraben-related products) was associated with 220% (95% CI: 99,

400%) higher Σ parabens concentrations compared to the lowest quartile of product use (fewer than 5 products), accounting for demographics. Among non-avoiders, the increase in Σ parabens concentration comparing the highest quartile to the lowest quartile was larger (340%, 95% CI: 140, 700%). Notably, the range in concentrations spanned at least three orders of magnitude for each quartile of product use, and several participants in the lowest quartile of product use had paraben concentrations similar to those in the upper end of the concentration distribution for the highest quartile. This suggests that there are other sources of parabens not included in our survey.

Overall, participants who reported avoiding products with parabens on the label had significantly lower Σ parabens concentrations compared to those who did not avoid parabens (Fig. 2). The geometric mean (GM) was 37% (95% CI: 51, -19%) lower among avoiders compared to non-avoiders based on a univariate censored regression model. However, for all of the products, nonusers had the lowest GM concentrations, users avoiding parabens had somewhat higher concentrations, and users not avoiding had the highest concentrations (Figure S5a). Differences were more pronounced at the 75th percentile. Participants who used a product that was judged *a priori* to be paraben-related and did not avoid parabens had significantly higher concentrations of Σ parabens than non-users of the product for all products except for shaving cream. Participants who used the products and did try to avoid parabens had significantly higher concentrations than nonusers only for the summary variables “any leave-on hair product” and “any products with paraben ingredients” and for body lotions, face cream, other leave-on hair

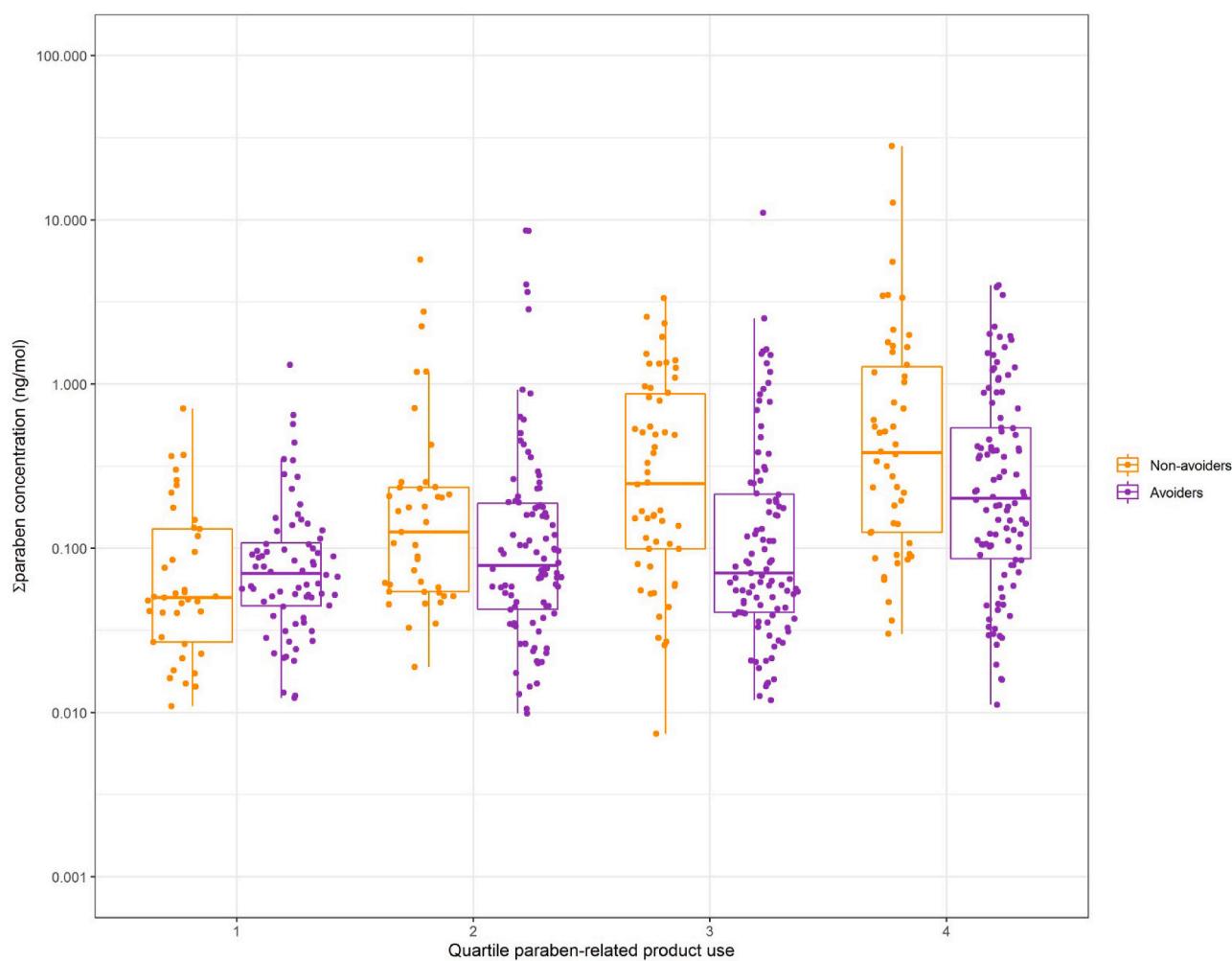


Fig. 1. Σ paraben concentrations by quartile personal care product use for non-avoiders and avoiders. Non-avoiders: Q1 = 0 to 4 products; Q2 = 5 to 7 products; Q3 = 8 to 10 products; Q4 = 11 to 17 products. Avoiders: Q1 = 0 to 4 products; Q2 = 5 to 7 products; Q3 = 8 to 10 products; Q4 = 11 to 17 products.

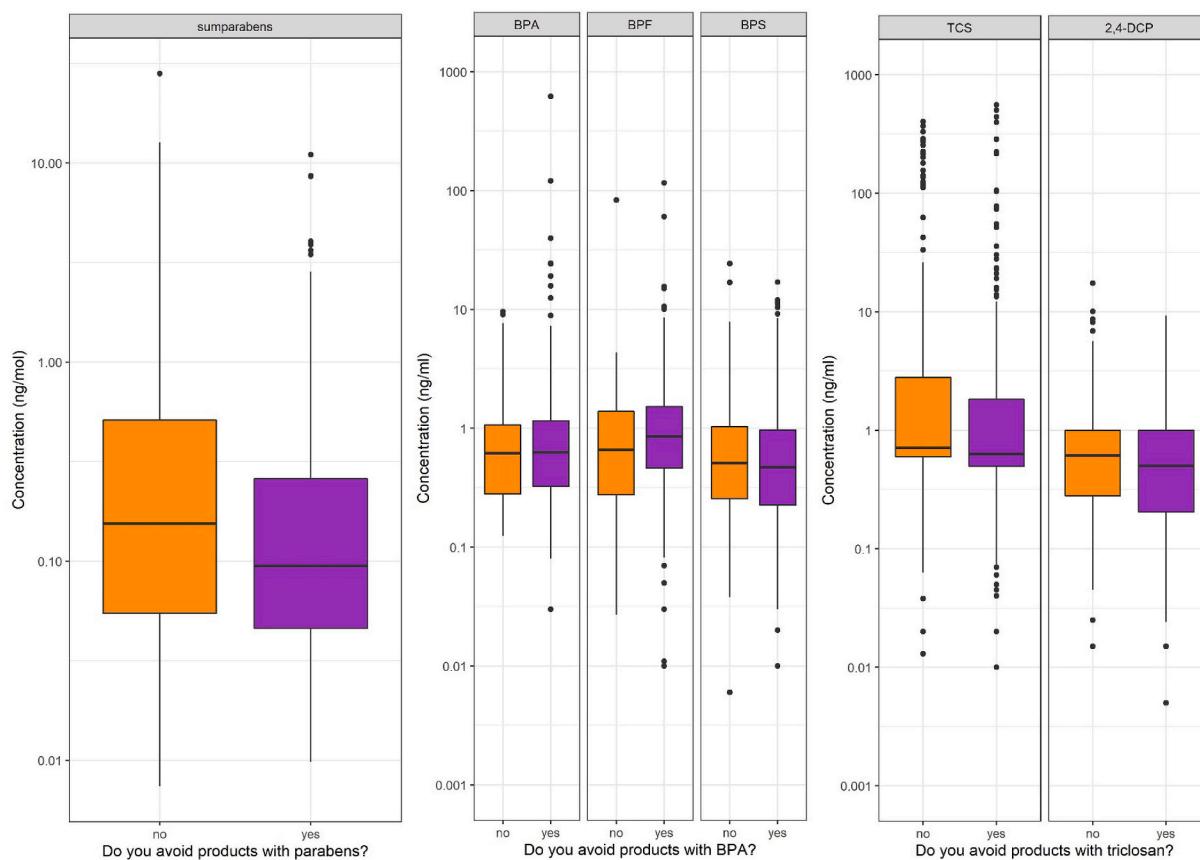


Fig. 2. Distribution of urinary concentrations by avoidance of particular chemicals. Significant difference in concentrations between non-avoiders (orange) and avoiders (purple) of parabens, triclosan, and 2,4-dichlorophenol. Participants were asked whether or not they avoided certain chemicals when selecting products. Participants were asked if they avoided triclosan or “antibacterial” or “antimicrobial” products. Note log scale on y-axis. Nondetects are plotted at the MRL. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

products, mascara, and sunscreen.

Consistent with the urine results, participants who said they avoid parabens also reported fewer products with parabens on the label during the label-checking portion of the survey (Figure S6). Interestingly, a higher proportion of paraben-avoiders used face cream, lip balm, lipstick, any makeup, and hair conditioner in the previous 24 h compared to non-avoiders. This may reflect that these users want to continue using the product and seek to minimize their exposure by scrutinizing ingredients (*i.e.*, becoming avoiders).

To quantify the change in exposure associated with each product, while adjusting for other products and demographics, we estimated change in urine concentration resulting from use of each product type, including avoidance and the interaction between avoidance and other product use and demographics as covariates in the model (Fig. 3). We estimated change in concentrations associated with each product use for both avoiders and non-avoiders. Among non-avoiders, use of body lotions, face cream, hand lotions, and lipstick significantly increased paraben concentrations. In contrast, concentrations were not elevated among avoiders who used these same products. Many products that were associated with higher concentrations in the previous model (Figure S5a) were no longer associated with significantly higher concentrations even among non-avoiders. Confidence intervals around percent change in concentration estimates for non-avoiders are typically wider than for avoiders, which likely reflects variability in product composition (*i.e.*, concentration of parabens in the product) or could reflect different use habits (*e.g.*, frequency, method of application). Interestingly, lipstick was associated with lower Σparabens among avoiders. This is presumably due to chance or to a behavior not captured in our study; for example, lipstick users who are trying to avoid parabens

may be particularly diligent avoiders.

3.4.2. Bisphenols

Participants who reported avoiding BPA did not have significantly lower BPA, BPF or BPS concentrations in their urine (Fig. 2), even though they reported multiple behaviors expected to reduce BPA exposure. Participants who avoid BPA on product labels were less likely to use plastic water bottles, drink a beverage from a metal can, and heat food in a plastic container in the previous 24 h compared to non-avoiders (Figure S6).

Participants who avoided BPA but used canned food in the last 24 h had a significantly lower GM BPS compared to those who did not and participants who did not avoid BPA and ate fast food had a lower GM BPF compared to those who did not (Figure S5b). We did not see other significant differences in GM concentrations of BPA, BPF, and BPS between users of BPA products and non-users, either among avoiders or non-avoiders. However, when we combine avoiders and non-avoiders, BPA concentrations were significantly higher for participants eating canned food and BPS concentrations significantly lower for participants for participants consuming canned beverages within 24 h compared to nonusers (Figure S8).

In interaction models adjusted for other product use, consuming food or a beverage from a metal can in the last day was associated with significantly higher BPA concentrations among non-avoiders (Figure S9a). Non-avoiders who ate fast food or take out or consumed canned beverage had higher BPS concentrations. In two instances, use of a BPA-related product was unexpectedly associated with lower BPS concentrations, likely because of an influential variable that we did not collect. BPF concentrations were not significantly associated with any

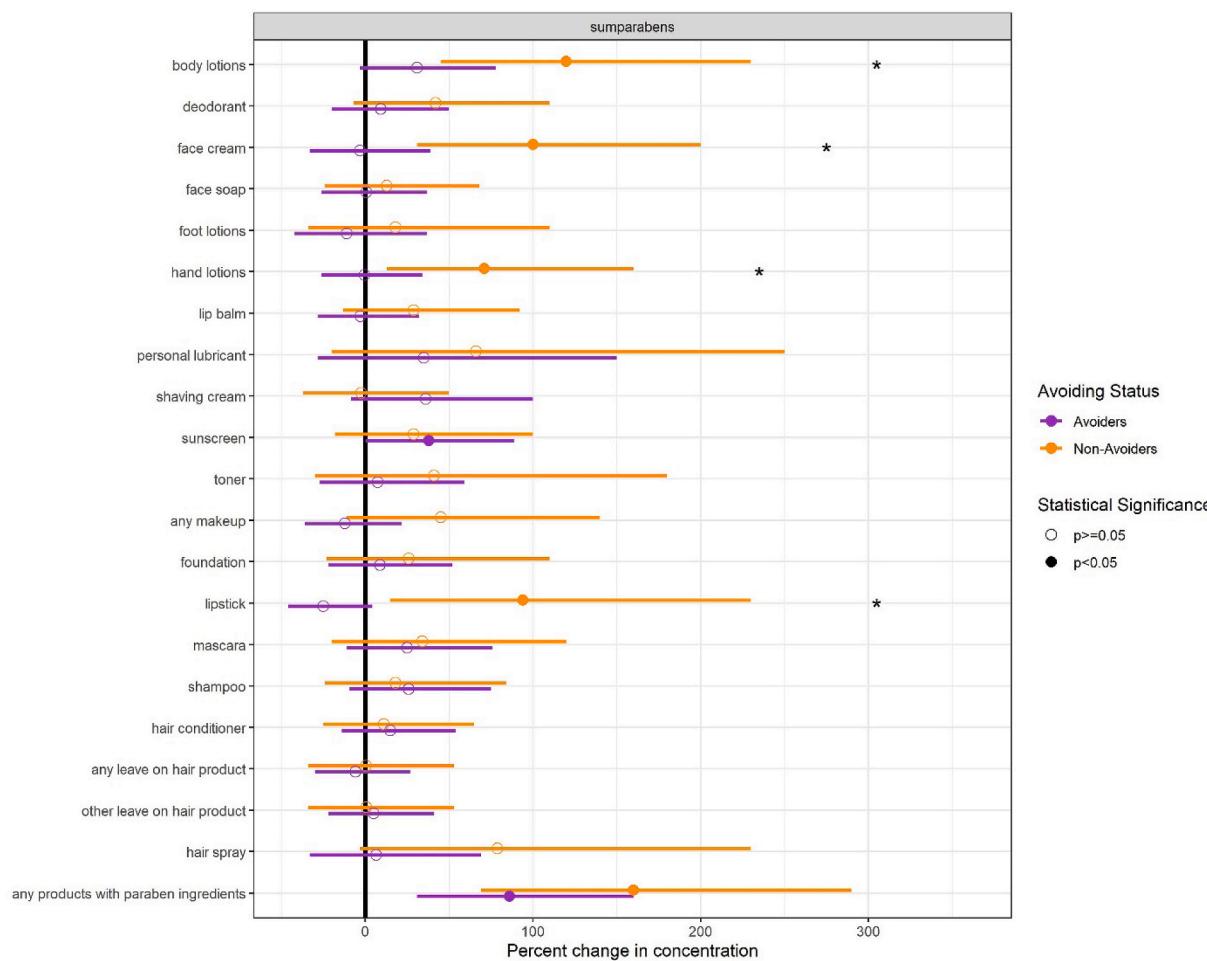


Fig. 3. Percent difference in Σ paraben concentrations associated with certain exposure behaviors in the last 24 h for participants who avoid parabens and those who do not. Models include weighted product count for other products, age (continuous), gender (binary: male, female), race (binary: non-Hispanic White, not non-Hispanic White), and education level (binary: college or less, graduate degree) as covariates. Asterisk indicates a significant interaction (p interaction < 0.05).

BPA-related product for either avoiders or non-avoiders, although the interaction between avoidance and plastic water bottle use was significant.

3.4.3. Triclosan and 2,4-dichlorophenol

Participants who avoided “triclosan,” “antibacterial,” or “antimicrobial” products had significantly lower (-45% , 95% CI: -62 , -18%) GM concentrations of triclosan and its degradation product 2,4-dichlorophenol (-31% , 95% CI: -45 , -12%) compared to non-avoiders (Fig. 2). Triclosan avoiders were less likely to use cleaning products at least weekly or to use hand soap, disinfectant wipes, disinfectant spray, or “any products labeled with triclosan” in the previous 24 h compared to non-avoiders (Figure S6).

Among non-avoiders, use of several triclosan-related products was associated with significantly higher concentrations of triclosan compared to nonusers who avoided and did not avoid triclosan (Fig. 4). These products include bar soap, deodorant, face soap, and disinfectant wipes. Concentrations were also higher among non-avoiders who cleaned at least regularly (once per week). There were fewer significant differences in 2,4-dichlorophenol concentrations.

In models adjusted for other product use and demographics, use of any products containing triclosan or labeled as “antibacterial” or “antimicrobial” significantly increased triclosan concentrations among both participants who did and did not avoid triclosan (Figure S9b). 2,4-dichlorophenol (a degradant of triclosan) concentrations were significantly higher among non-avoiders using any products with triclosan.

Non-avoiders, but not avoiders, using deodorant or disinfectant wipes had higher triclosan concentrations, although these differences were not significant. For 2,4-dichlorophenol, any cleaning and use of disinfectant wipes, in particular, was associated with higher 2,4-dichlorophenol concentrations only among participants avoiding triclosan suggesting a possible substitution effect (*i.e.*, triclosan avoiders inadvertently selecting a product with 2,4-dichlorophenol or related chemical).

3.4.4. 2,5-Dichlorophenol

A small number of participants reported using products in the previous 24 h that potentially contain 2,5-dichlorophenol or the parent chemical 1,4-dichlorobenzene: 1.2% reported using mothballs, 1.2% toilet bowl deodorizers, 10% toilet bowl cleaners, 27% surface cleaners, and 4.3% tampons (Table S1). Only use of moth balls was associated with a significant increase (460%, 95% CI: 61, 1900%) in 2,5-dichlorophenol concentrations in a model adjusted for other product use and demographics (Figure S10).

3.4.5. Benzophenone-3

Using more products was associated with significantly higher benzophenone-3 concentrations (Figure S11). Being in the highest quartile of product use (more than five benzophenone-3-related products) was associated with 140% (95% CI: 67, 240%) higher benzophenone-3 concentrations compared to being in the lowest quartile (zero products). Benzophenone-3 is added to some sunscreens and other personal care products as a UV filter. Participants who reported

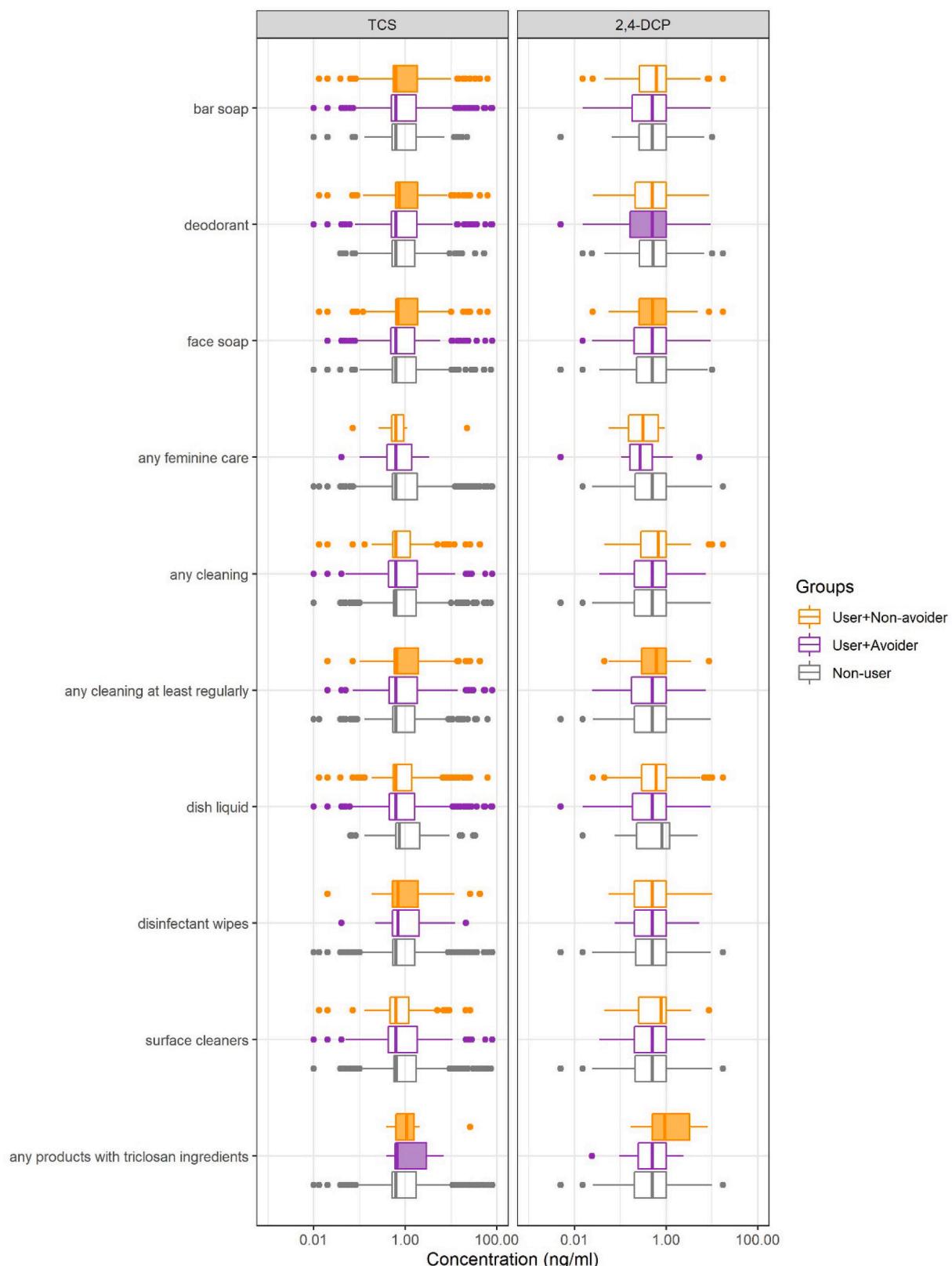


Fig. 4. Distribution of triclosan and 2,4-dichlorophenol concentrations for participants who do not use a product (non-user), avoiders who use a product, and non-avoiders who use a product. Shaded boxplots indicate significant ($p < 0.05$) difference from non-user. "Any products with triclosan ingredients" determined from label reading by participant. Nondetects plotted at the MRL.

using sunscreen in the previous 24 h (28%) had 120% higher (95% CI: 57, 210%) concentrations than those who did not (Fig. 5). Participants who used body lotion, face cream, lip balm, and “any products with benzophenone-3 ingredients” also had significantly higher concentrations of benzophenone-3. In addition, participants who drank out of a plastic water bottle in the previous 24 h had 58% (95% CI: 18,110%) higher concentrations than those who did not.

3.5. Participants with lowest exposures

Participants avoiding all four chemical groups (BPA, parabens, triclosan, and fragrances) compared to those who did not avoid all four groups had nearly twice the odds of being in the lowest quartile of cumulative rank, the sum of the participants' urine concentration ranks across all chemicals (OR: 1.9; 95% CI: 1.3, 2.8).

3.6. Report back

All but two participants consented to receive their personal results reports, and 36 of them contacted the study team to discuss their results. They often expressed surprise or wondered why they had certain chemicals in their sample. Many described actions—such as eating organic, not drinking from plastic water bottles, and choosing products based on labeled ingredients—that they adopted to avoid chemicals that were detected in them. Seven participants who contacted us about a high chemical concentration were able to identify a specific product

containing the corresponding chemicals.

4. Discussion

We conducted a crowdsourced biomonitoring study for selected EDCs in urine to address two central goals: First, to make information about personal exposure concentrations more widely available, and, second, to learn how product use influences exposure and investigate whether consumers who are trying to avoid certain chemicals have lower exposures than those who do not. We enrolled more than 700 volunteers to test urine samples for phenolic compounds. We collected survey data on their cleaning habits, use of consumer products, and efforts to avoid parabens, triclosan, bisphenols, and fragrances.

As we anticipated, the crowdsourced design engaged a large number of participants who were actively taking steps to avoid specific chemicals in consumer products, enabling us to investigate the efficacy of these strategies. Overall, participants in this study had lower urine concentrations than a representative sample of the US population for parabens, BPA, triclosan, and benzophenone-3 but not BPF and BPS. No one was able to completely avoid these chemicals.

Consumers can aim to lower their exposures by avoiding or reducing their use of certain products likely to contain the chemicals and by reading labels to avoid chemicals listed on the products they do use. Our results show these strategies are effective for parabens, triclosan, and benzophenone-3. Participants who used fewer products had lower urine concentrations of related chemicals. Additionally, product-users who

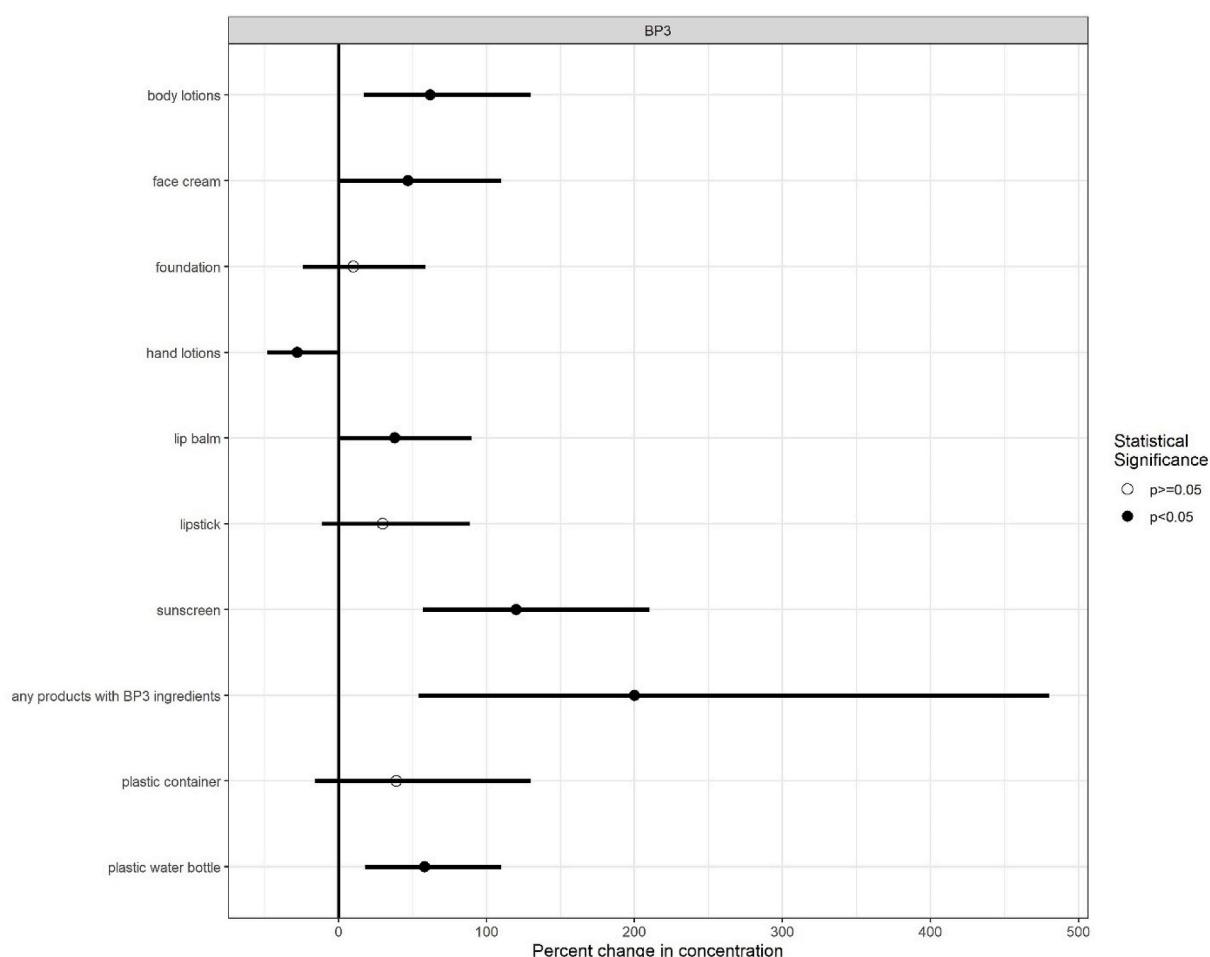


Fig. 5. Percent difference in benzophenone-3 (BP-3) concentrations associated with certain exposure behaviors in the last 24 h for all participants. Models include a weighted product count for all other products as a covariate. Models include weighted product count for other products, age (continuous), gender (binary: male, female), race (binary: non-Hispanic White, not non-Hispanic White), and education level (binary: college or less, graduate degree) as covariates.

scrutinized ingredient labels to avoid certain chemicals had lower exposures relative to those who did not. Participants who avoided all four ingredient groups—parabens, triclosan, bisphenols, and fragrances—were nearly twice as likely as others to be in the lowest quartile of cumulative exposure. However, concentrations spanned orders of magnitude even among participants who avoided all the chemicals we asked about, and the highest exposures among avoiders were sometimes higher than among non-avoiders.

Chemical avoidance was most effective for parabens. For most products, users who avoided parabens on ingredient labels had lower paraben concentrations compared to non-avoiders. Differences were largest for use of body lotions, face cream, hand lotions, and lipstick. These results suggest that, at least for these products, participants can find products that do not contain parabens or have lower levels of them. Findings are consistent with our previous research, which showed that parabens are more likely to appear on product labels compared to many other chemicals (Dodson et al., 2012; Helm et al., 2018).

Chemical avoidance was not effective for BPA and related chemicals. Although 86% of participants in this study reported avoiding BPA, urine concentrations of BPA, BPF, and BPS were not significantly different among avoiders and non-avoiders. BPA avoiders were less likely to use plastic water bottles, drink out of a metal can, or heat food in plastic (behaviors expected to be associated with BPA); however, a similar percentage of avoiders and non-avoiders reported eating canned food, even though BPA has been associated with canned food previously (Hartle et al., 2016; Peng et al., 2019). Drinking out of a metal can was associated with higher BPA concentrations, particularly among non-avoiders. Results suggest that there are other sources of BPA that we did not capture and that participants may not be aware that canned food is a source. Avoiding BPA is difficult, because BPA-containing products need not be labeled.

The lack of association between BPS and BPF concentrations with reported use of BPA-related products suggests that these chemicals are not direct replacements for BPA and that these chemicals have other uses that we have not yet identified. Studies have shown, for example, that handling thermal paper receipts results in higher BPS concentrations (Ndaw et al., 2018; Thayer et al., 2016), but we did not ask about receipt handling. We observed a nonsignificant increase in BPS concentrations among BPA-non-avoiders who reported eating fast food or food from take-out containers. This finding is consistent with tests showing BPS in food contact materials (Liao et al., 2012).

Associations between product use and elevated urine concentrations in this study are largely consistent with previous studies, although these associations are diminished among participants trying to avoid certain exposures. Similar to other studies, we observed an association between use of body lotions and increased paraben concentrations (Braun et al., 2014; Fisher et al., 2017), and between body lotions or sunscreen and higher benzophenone-3 (Ashrap et al., 2018; Bethea et al., 2020). Our finding that drinking a beverage in a metal can increased BPA concentrations, particularly among non-avoiders, is consistent with a previous study that showed a 1600% increase in BPA concentrations 2 h after consuming a beverage from a can compared to a glass bottle (Bae and Hong, 2015). Use of deodorant was associated with higher triclosan concentrations in our study, and triclosan is known to be an antimicrobial and preservative used in personal care products including deodorant (Goldsmith et al., 2014). Although use of mothballs was uncommon in our study, this activity was associated with significantly higher 2,5-dichlorophenol concentrations, and 2,5-dichlorophenol is a metabolite of 1,4-dichlorobenzene, which is found in mothballs (HSDB, 2019; Yoshida et al., 2002).

This study adds to knowledge about the role of consumer products as sources of chemical exposures by investigating a large group of participants and including many who were trying to reduce their exposures through product choices. However, we were limited in our ability to relate product choices to exposures, because nondisclosure of ingredients by manufacturers made it difficult to know what questions to

ask in our survey. Except for cosmetics, many common consumer products lack information on their chemical constituents, which may explain why we were unable to adequately identify sources of bisphenols and 2,5-dichlorophenol. In contrast, since personal care products tend to have more complete labeling of ingredients, we were better able to identify products associated with higher paraben levels. Another limitation is exposure misclassification due to the timing of urine collection in relation to the information collected in the survey about product use in the previous 24 h. Participants were asked to complete the 24-h product use survey just after collecting their morning urine sample, which marks the end of the 24 h. For chemicals like the bisphenols, which are rapidly eliminated from the body, the association between some product use and urine concentrations for use of products in the first 6–8 h of the previous day may be underestimated. However, because parabens and triclosan have longer biological half-lives, we expect the previous evening sample captured exposure during the previous day. We adjusted for age, gender, race/ethnicity and education status in our evaluation of the relationship between product use and urine concentrations, and also included an overall product use variable. A limitation of our study is that we did not collect information about other potential correlates such as BMI and smoking. We did not adjust for urinary dilution, which may be a limitation; however, we asked participants to collect samples at standardized times to mitigate this potential issue. Finally, our findings may not be generalizable to all populations. People of color were under-represented, so although we asked about hair products that are marketed to and used by Black women, we did not have adequate power to detect associations. Men were somewhat under-represented, and those with graduate degrees were over-represented. We offered free sampling kits through allied organizations, including Resilient Sisterhood Project and Black Women for Wellness, among others, and we are undertaking interviews with these groups to understand how to better include their communities in the future.

Our study asked about a range of behaviors and product choices that follow the exposure-reduction advice provided by NIH-supported studies, such as the Breast Cancer and the Environment Research Program (BCERP, 2016) and PROTECT Superfund Research Program (PROTECT, 2020), and by other research-based resources, such as the Endocrine Society (Endocrine Society, 2020) and Silent Spring Institute's Digital Exposure Report-Back Interface (DERBI) (Boronow et al., 2017) and Detox Me smartphone application (Silent Spring Institute, 2020), among others. These resources provide general decision-making guidance, such as advice to choose stainless steel or glass rather than plastic and avoid fragrance and specific ingredients on labels. Our results support the efficacy of this advice, particularly for parabens and antimicrobials, and show that consumers can voluntarily adopt recommended actions on their own, outside of an intervention study, and achieve lower urine concentrations of many chemicals than typical Americans represented in NHANES. We also found exceptions—chemicals that were not lower in avoiders than non-avoiders (BPA, BPF and BPS) and instances in which avoiders had very high concentrations of a chemical, most likely from a source we did not ask about. These anomalies show that in order for consumers to avoid specific chemicals, they need more detailed ingredient lists on a much wider range of products. While the US Food and Drug Administration (FDA) requires intentionally added ingredients to be listed on cosmetics (Food and Drug Administration, 1938, 1967) and EPA requires labeling of registered pesticides and disinfectants (Environmental Protection Agency, 1972), there are few labeling regulations for other common consumer products such as cleaners and durable goods like plastic containers or treated performance fabrics. Policy efforts to increase transparency of product ingredients can help consumers and retailers select products with fewer EDCs or carcinogenic chemicals. However, this approach creates an unrealistic burden on consumers to learn the names and health implications of the thousands of ingredients that would be listed. Regulation that restricts chemicals with potential

toxicity from use in consumer products could address these challenges.

Declaration of competing interest

The authors declare they have no actual or potential competing financial interests. This study is supported by charitable contributions to Silent Spring Institute, a nonprofit research organization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijheh.2020.113624>.

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