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# Randomised controlled trial of real-time feedback and brief coaching to reduce indoor smoking

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## ABSTRACT

**Background** Previous secondhand smoke (SHS) reduction interventions have provided only *delayed* feedback on reported smoking behaviour, such as coaching, or presenting results from child cotinine assays or air particle counters.

**Design** This SHS reduction trial assigned families at random to brief coaching and continuous real-time feedback (intervention) or measurement-only (control) groups.

**Participants** We enrolled 298 families with a resident tobacco smoker and a child under age 14.

**Intervention** We installed air particle monitors in all homes. For the intervention homes, *immediate* light and sound feedback was contingent on elevated indoor particle levels, and up to four coaching sessions used prompts and praise contingent on smoking outdoors. Mean intervention duration was 64 days.

**Measures** The primary outcome was 'particle events' (PEs) which were patterns of air particle concentrations indicative of the occurrence of particle-generating behaviours such as smoking cigarettes or burning candles. Other measures included indoor air nicotine concentrations and participant reports of particle-generating behaviour.

**Results** PEs were significantly correlated with air nicotine levels (r=0.60) and reported indoor cigarette smoking (r=0.51). Interrupted time-series analyses showed an immediate intervention effect, with reduced PEs the day following intervention initiation. The trajectory of daily PEs over the intervention period declined significantly faster in intervention homes than in control homes. Pretest to post-test, air nicotine levels, cigarette smoking and e-cigarette use decreased more in intervention homes than in control homes.

**Conclusions** Results suggest that real-time particle feedback and coaching contingencies reduced PEs generated by cigarette smoking and other sources.

**Trial registration number** NCT01634334; Post-results.

## INTRODUCTION

Concentrations of fine particulate matter (<2.5 µm; $PM_{2.5}$) can be elevated by indoor activities: smoking tobacco or marijuana; and burning wood, candles, incense or food.[1–4] Children are especially susceptible to respiratory distress from exposure to fine particles.[5–7]

In addition to particulate matter, secondhand smoke (SHS) contains over 7000 chemicals, at least 98 of which are toxic.[8 9] About 40%–50% of children are exposed to SHS in the USA and globally,[10–12] increasing risk of cancer, respiratory and cardiovascular disease, and other adverse health effects.[13 14] SHS can sensitise children to nicotine, possibly increasing risk of smoking in adolescence.[15 16] Children's greatest risk of SHS exposure is in the home.[17–19]

SHS in homes accumulates in dust and on surfaces, resulting in the persistent residue known as thirdhand smoke (THS).[20] THS includes toxicants and carcinogens found in SHS, plus additional toxic compounds generated through reaction with ambient oxidants.[20] Exposure to THS occurs through off-gassing from surfaces, dermal contact with contaminated surfaces and ingestion of contaminated objects and dust. THS toxicants have been found at significantly increased levels months after cigarettes have been smoked, *making SHS prevention even more important to prevent THS exposure*.[21–24]

Most SHS trials designed to reduce indoor smoking have used coaching to move smoking outdoors, encourage cessation or create home smoking bans,[21 25–27] confirmed by child cotinine levels in several studies.[28–31] Typically, coaches offer praise or criticism of participants' self-reported reduction in smoking, but seldom proximal in time to the emitted behaviour. A systematic replication of a coaching intervention for SHS exposure reduction across three sites demonstrated the generalisability of coaching to reduce indoor smoking.[32–34] The effectiveness of delayed feedback also has been investigated in studies using objective measures of child cotinine[35–39] or of air particle levels in the home.[37 38 40 41] However, feedback is most effective when delivered immediately and reliably.[42–45] Emerging technologies offer real-time assessment of fine particle levels in household air, enabling consistent immediate feedback and higher-fidelity reinforcing or punitive contingencies.[46]

We previously conducted a feasibility study of real-time particle feedback in several homes,[47] and a pilot investigation to select appropriate, mildly aversive auditory alerts as feedback.[48] Based on these studies, we designed Project Fresh Air, a randomised controlled trial, to test coaching combined with real-time auditory and visual

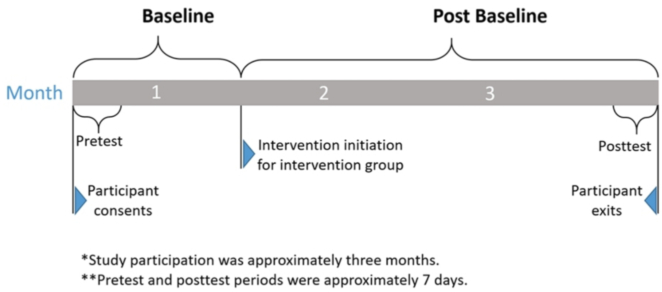


**Figure 1** Study timeline.

feedback following episodes of high indoor particle levels that indicated cigarette or marijuana smoking, and other activities such as burning incense. This report summarises the success of coaching and contingent light and sound feedback in reducing airborne-particle-generating behaviours, including cigarette smoking, in the home.

## METHODS

Details of the methods of the Project Fresh Air trial, including a Consolidated Standards of Reporting Trials diagram, are in our first published outcome report, which focused on average indoor particle levels, and demonstrated a decrease favouring the intervention group.[49] The current outcome report focused on behaviours that were directly targeted by the intervention—primarily indoor cigarette smoking, but also other behaviours capable of generating high concentrations of fine particles, such as smoking marijuana, and burning candles or incense. To objectively measure the target behaviours, we reviewed time series data from customised Dylos air particle monitors and identified 'particle events' (PEs), operationalised as any episode during which indoor particle counts rapidly increased to a high level and remained above ambient levels for 1 min or longer. Prior research showed that using a threshold of 15 000 counts per 0.01 $ft^3$ (53 million counts/$m^3$) of fine air particles (sized 0.5–2.5 µm in diameter), captured all indoor cigarette smoking events.[47] Due to the high time cost and human error associated with visually counting events on a graph, we developed a computer algorithm to count PEs. Online supplementary appendix 1 provides details on (a) visual identification of PEs; (b) how the computer algorithm captured the essential 'signature' of a PE; and (c) validation of the algorithm against the visual method.

### Participants

We recruited participants from local organisations during 2012 to 2015, enrolling 298 families. Study participation required: a parent or guardian 18 years or older; a smoker and a child under the age of 14 living in the home; English or Spanish speaker; and no plans of moving from San Diego County for at least 3 months.

Enrolment/randomisation criteria were ≥3 PEs in the home during an initial eligibility determination period (≥7 days) and one or more of the following: report of child exposure to SHS in the home; report of either indoor cigarette smoking, a partial indoor smoking ban or no indoor smoking ban; staff observation of tobacco smoking (or evidence of tobacco smoking) in the home.

### Study design

Assignment of sequentially consented participants to experimental condition was accomplished by randomising one participant to either the intervention (coaching and real-time feedback) group or the control group, and then assigning the next participant to the other group to ensure a 1-to-1 ratio.

Two specially designed Dylos (DC1700) air particle monitors were installed in participants' homes, one in the room nearest to where most smoking occurred and the other in the room where the child slept, as reported by the participant. Monitors continuously measured air particle levels during baseline, lasting on average 37.5±16.3 days and postbaseline lasting 61.8±24.3 days (figure 1). On the first day of baseline, we placed passive nicotine dosimeters within 2 feet of the monitors to measure air nicotine. After 7 days (at the end of the pretest week), staff collected the dosimeters and conducted an interview with the consented parent/guardian, including sociodemographics, SHS exposure and particle-generating behaviours during the prior 7 days. Seven days prior to study end, staff hung new nicotine dosimeters for the post-test week. On the final day, we conducted a second interview and collected nicotine dosimeters.

### Intervention

Based on *principles of behaviour*,[50] and our extension to the Behavioural Ecological Model,[51] the intervention was designed to reduce smoking in the home using real-time punishment contingencies (mildly aversive lights and sounds), social reinforcement contingencies (praise) and delayed graphic feedback. The contingency principle asserts that behaviour is selected as a function of the *consequences that followed previous similar behaviour*.[52] For example, the current intervention was designed to deliver aversive consequences almost immediately after a cigarette was lit indoors, in order to reduce future occurrences of lighting cigarettes indoors.

Air particle data transmitted via telemetry from intervention homes were reviewed by investigators several times each week, for a minimum of 1 week after the pretest, to determine when to begin the feedback. When consensus was reached that PEs were stable or increasing, staff scheduled the first coaching visit with intervention participants, during which they initiated real-time feedback by enabling the behavioural module[48] attached to each monitor to emit a slightly aversive brief audible alert and a solid yellow LED light when air particle counts breached 15 000 per 0.01 $ft^3$.[48] When particle counts reached 30 000 per 0.01 $ft^3$ (106 million counts/$m^3$), a red blinking LED and a louder, more aversive brief sound were produced. A steady green light was displayed, and no sound was emitted when particle levels were below the 15 000-count threshold.

During the intervention period, participants in the intervention group received up to four brief one-on-one coaching sessions where staff presented participants with time-series graphs of household air particle levels for the past week and discussed strategies to respond to the real-time feedback. These sessions used motivational interviewing and goal setting to help participants move smoking outside and reduce other particle-generating behaviours. Coaches promoted leaving the home before lighting a cigarette and *praised* reports of reducing indoor smoke by smoking outside, opening windows, using kitchen exhaust fans when cooking and keeping windows and doors shut when smoking outside near the home.

### Measures

#### Particle counts

Each second, air monitors counted the number of fine particles per 0.01 $ft^3$ of air. Particle counts were averaged every 10 s and transmitted via a wireless network to a cloud-based server that enabled visualisation in real time. Data analysts reviewed


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**Table 1** Coefficients of correlations and partial correlations of objective and self-reported measures during the pretest and post-test weeks with particle events counts during the same time periods

| | Correlation coefficients | P value | Partial correlation coefficients* | P value |
|---|---|---|---|---|
| Objective measure | | | | |
| Air nicotine† | 0.595 | **<0.001** | – | – |
| Self-reported measures‡ | | | | |
| Smoked cigarettes indoors | 0.508 | **<0.001** | 0.391 | **<0.001** |
| Smoked marijuana indoors | 0.347 | **<0.001** | 0.169 | **0.010** |
| Burned incense or candles | 0.214 | **<0.001** | 0.145 | **0.028** |
| Used electronic cigarettes indoors | 0.173 | **0.005** | 0.126 | 0.056 |
| Fried with oil | 0.084 | 0.146 | 0.020 | 0.778 |
| Swept/dusted/vacuumed | 0.080 | 0.168 | 0.115 | 0.082 |
| Burned food | 0.028 | 0.628 | 0.046 | 0.490 |

Bold values indicate p<0.05.
*We computed partial correlations from models that control for all other self-reported measures.
†Average concentration (μg/m$^3$) during the assessment weeks.
‡How often the behaviour occurred in the home during the assessment weeks.

raw time-series data for anomalies. Across all homes, days with data that were indicative of monitor malfunction (n=182 days; 0.63%) were removed along with 1286 (4.45%) days with ≥5 consecutive hours of missing data, leaving 27443 days (94.92%) available for analysis. Missing data were typically due to interruption of electrical power, while monitor malfunctions were usually due to dirty monitors. We amended the study protocol to ensure thorough cleaning of monitors prior to reinstallation in subsequent homes.

### Interview measures

During pretest and post-test interviews, participants reported the number of times they smoked/used cigarettes, other tobacco products, marijuana or e-cigarettes indoors over a 7-day period (1–3 times, 4–6 times, 7–9 times, ≥10 times), and the number of days (0–7) they burned incense/candles, fried with oil, swept/dusted/vacuumed the house or burned food.

### Air nicotine

Nicotine dosimeter assays[53] were conducted by liquid chromatography tandem mass spectrometry using electrospray ionisation, and used to estimate average air nicotine concentration (μg/m$^3$).

## Statistical analysis

We computed analyses using Stata V.14,[54] SPSS V.25,[55] and R V.1.0.136.[56] Intent-to-treat analysis[57] was used unless otherwise specified. All tests were two-tailed (alpha=0.05).

## PE analysis

We derived the PE outcome measure from counts by the monitor in the room nearest to where the participant reported that the most smoking occurred. Correlations of PEs with indoor air nicotine concentrations and reported particle-generating behaviours were computed for data from pretest and post-test, controlling for within-subjects repeated measures. PEs during baseline and postbaseline were described by group, using the IQR and geometric means.

To assess the intervention effect on PEs, an *interrupted time-series* (ITS) approach was used to analyse the repeated measures of PEs before and after the point of intervention.[58 59] The ITS procedure is appropriate for particle data collected continuously over approximately 3 months and for an intervention that imposed an abrupt discontinuity in environmental consequences for participants in the intervention group. ITS analyses have three notable advantages over comparing aggregated pre and post measures for control and intervention groups. For both intervention and control groups, the ITS analysis enables estimates of (1) the time-course of the outcome before the intervention began, providing a more accurate trajectory of the outcome in the absence of the intervention; (2) the change in outcome level at the intervention point, allowing inferences about effects immediately following initiation of the intervention; and (3) the time-course of the outcome across the intervention period, allowing inferences about trajectories during the intervention free from the influence of preintervention data.[60]

ITS analyses require specification of the date on which the intervention began[58]; therefore, we centred the data on the date of the first coaching visit for the intervention group (day zero), when real-time feedback was activated. As the control group did not receive an intervention, each control home's 'intervention' start date (day zero) was set so that the number of days in the baseline period matched that of the intervention home with which it was enrolled/randomised.

We implemented ITS analyses using a generalised linear mixed effects model with random intercepts and random slopes to account for differences in individual-level initial PEs and changes in PEs over time. These models handle data 'missing at random' and data measured over irregular time intervals.[61] Due to overdispersion, we modelled PEs per day assuming a negative binomial distribution. We used an unstructured covariance structure to account for daily repeated measures within each home. The following regression model was fit:

$$\begin{aligned} ln(Y_{ti}) &= \beta_0 + \beta_1 t + \beta_2 X_{ti} + \beta_3 t X_{ti} + \beta_4 Z_i \\ &+ \beta_5 t Z_i + \beta_6 Z_i X_{ti} + \beta_7 t Z_i X_{ti} + u_{0i} + u_{li} t + e_{ti}, \end{aligned}$$

where $Y_{ti}$ is the number of PEs for home $i$ on day $t$ (where $t$=1 on postbaseline day 1), $t$ is the number of days from the intervention start, $X_{ti}$ is a binary variable indicating the baseline ($X_t$=0) or postbaseline period ($X_t$=1) for home $i$, $Z_i$ is an indicator for group (1=control, 0=intervention), $tX_{ti}$, $tZ_i$, $Z_iX_{ti}$ and $tZ_iX_{ti}$ are interactions of the respective variables, $u_{1i}t$ and $e_{ti}$ are respectively the between-home intercept and slope error terms, and $e_{ti}$, is the residual for each observation.

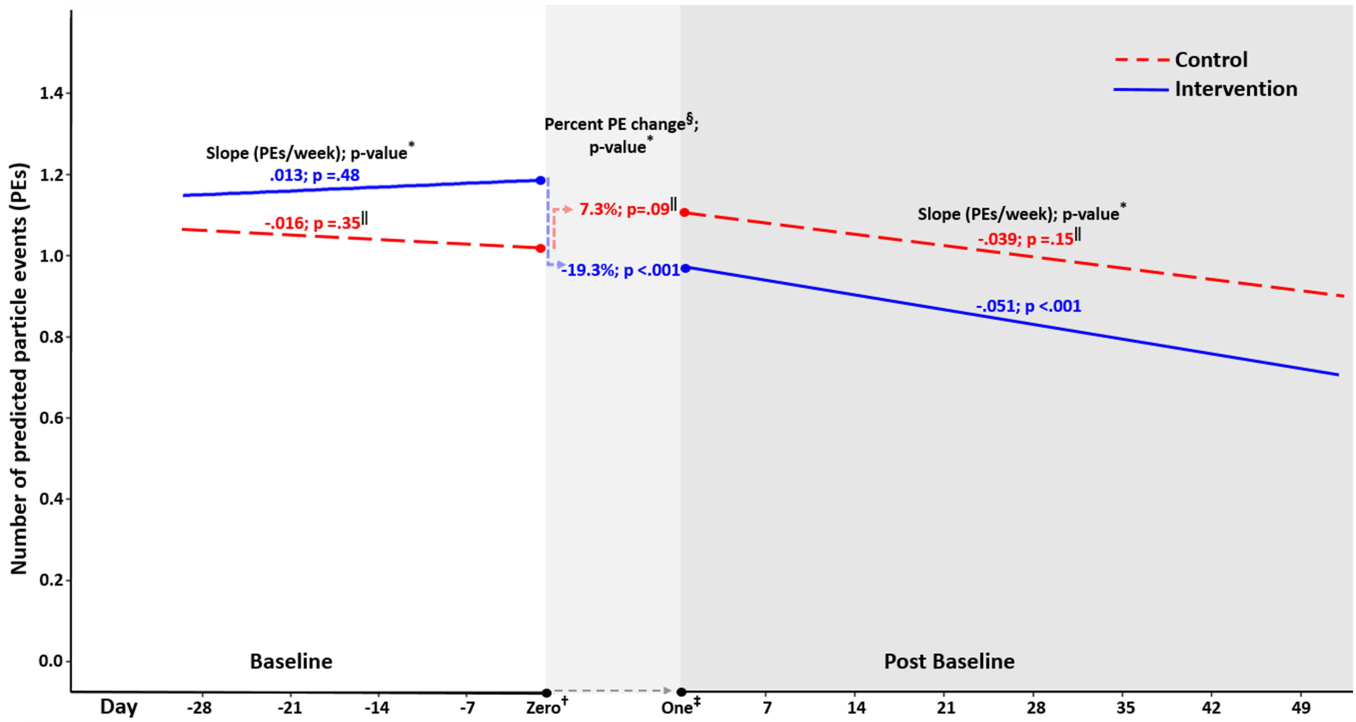
## Analysis of air nicotine and reported measures of particle-generating behaviours

All variables were log transformed to approximate a normal distribution. To accommodate repeated measures within homes, we tested differential group-by-time changes in means using the generalised estimating equations (GEE) procedure in Stata (xtgee), specifying a Gaussian distribution and unstructured correlation structure.

## RESULTS

## Baseline characteristics

The mean age of enrolled adults was 32.94 years (SD=8.54), with 37.24% having a high school education or less. Households had a mean of 4.86 occupants (SD=1.59), with an average of 2.66 adults (SD=1.08) and 2.19 children (SD=1.18). Enrolled children had a mean age of 4.06 (SD=3.58); almost half (46.98%) were female. The median annual income was between




* *p*-value testing difference from 0
† Day Zero = the last day of the Baseline period, the day during which light and sound feedback was activated in intervention homes
‡ Day One = the day following Day Zero; the first day of the Post Baseline period
§ Percent PE change from Day Zero to Day One
|| Slope, percent change, and *p*-value for control group are from results of linear interrupted time-series analysis using alternative coding of indicator for group (i.e., 0=control, 1=intervention); Supplementary Table 3
¶ While all available data were used in computing the estimates on which the figure was based, the displayed line plot spans from day -35 in Baseline to day 56 in Post Baseline, reflecting approximately the mean number of days spent in each of those time periods by the study cohort (N = 298).

**Figure 2** Estimated number of particle events per week during baseline and postbaseline, by group. Results from linear interrupted time-series analysis. N=298 homes.

\$20 000 and \$29 999. A mean of 1.60 smokers (SD=0.77) lived in the homes. (see online supplementary table 1) (additional sample characteristics are in table 1 of: https://doi.org/10.1016/j.amepre.2017.10.017).

## PE results

### Descriptives

Online supplementary table 2 shows the geometric mean and distributions of PEs per day for each group during the baseline and postbaseline periods. Median PEs per day for the control and intervention groups respectively were 0.55 and 0.60 during baseline and 0.56 and 0.47 during postbaseline. Details of distributions are in online supplementary table 2.

### Validation correlations

PEs per day were correlated with air nicotine levels in the expected direction and with reported behaviours that typically generate PEs. The correlation with PEs was strongest for air nicotine and for indoor cigarette smoking (table 1).

### Interrupted time-series

#### *During baseline*

For the intervention group, the slope of the baseline PE trajectory was not significantly different from zero ($\beta_1$=0.001: p=0.48, figure 2 and table 2). Neither the intercepts ($\beta_4$=−0.156: p=0.31) nor the slopes ($\beta_5$=−0.003: p=0.25) of the baseline PE trajectories were significantly different by group, consistent with random assignment.

#### *Immediately after intervention initiation*

There was a significant 19.35% reduction in the predicted number of PEs from the last baseline day (day zero) to the first postbaseline day (day 1) for the intervention group ($\beta_2$: p<0.001; this per cent change in intervention-group effect was computed as: $[e^{\beta2} - 1] \times 100$; table 2). For the control group, the number of PEs on the first day of postbaseline was slightly (7.36%) higher than on the last day of baseline, but the increase was not statistically significant (p=0.09; see online supplementary table 3; per cent change in control-group effect = $[e^{\beta2+\beta6} - 1] \times 100$; table 2). The immediate intervention effect—defined as the difference between the effect in the intervention group ($e^{\beta2}$) and the effect in the control group ($e^{\beta2+\beta6}$) relative to the effect in the control group—quantified the change in PEs attributable to the intervention immediately following coaching visit 1 and initiation of real-time feedback, yielding a 24.87% larger reduction in PEs within the intervention group versus controls ($\beta_6$: p<0.001; see online supplementary table 3; computed as: $\{[e^{\beta2} - e^{\beta2+\beta6}]/e^{\beta2+\beta6}\} \times 100$; table 2).

#### *During postbaseline*

For the intervention group, the slope of the trajectory of estimated PEs significantly decreased during postbaseline ($\beta_3$: p<0.001). There was a significant between-group difference in the change in the slope of the trajectory from the baseline to the postbaseline period, with the intervention group having a larger decrease in slope ($\beta_7$: p=0.04).

**Table 2** Results for linear interrupted time-series analyses of group by time changes in daily particle events (PEs) (n=298)

| Coefficient* | Interpretation | Estimate | 95% CI | P value |
|---|---|---|---|---|
| $\beta_0$ | Intercept of the PE trajectory† during baseline for the intervention group. | 0.172 | −0.042 to 0.386 | 0.114 |
| $\beta_1$ | Slope of the PE trajectory† during baseline for the intervention group. | 0.001 | −0.002 to 0.004 | 0.484 |
| $\beta_2$ | Difference in baseline to postbaseline estimated PEs on the first day of postbaseline for the intervention group. | −0.214 | −0.294 to −0.134 | **<0.001** |
| $\beta_3$ | Difference in slope of PE trajectory† from baseline to postbaseline for the intervention group. | −0.007 | −0.011 to −0.004 | **<0.001** |
| $\beta_4$ | Between-group difference in the baseline PE trajectory† intercept. | −0.156 | −0.459 to 0.147 | 0.313 |
| $\beta_5$ | Between-group difference in slope of the PE trajectory† during baseline. | −0.003 | −0.007 to 0.002 | 0.249 |
| $\beta_6$ | Between-group difference in the baseline to postbaseline change in estimated PEs on the first day of postbaseline. | 0.285 | 0.171 to 0.398 | **<0.001** |
| $\beta_7$ | Between-group difference in the baseline to postbaseline change in PE trajectory† slopes. | 0.005 | 0.000 to 0.010 | **0.043** |

*Coefficients are from the following equation with the intervention group coded as the reference group: $ln(Y_{ti}) = \beta_0 + \beta_1 t + \beta_2 X_{ti} + \beta_3 tX_{ti} + \beta_4 Z_i + \beta_5 tZ_i + \beta_6 Z_i X_{ti} + \beta_7 tZ_i X_{ti} + u_{0i} + u_{1i} t + e_{ti}$, where $Y_{ti}$ is the number of PEs for home $i$ on day $t$ (where $t$=1 on postbaseline day 1), $t$ is the number of days from the intervention start, $X_{ti}$ is a binary variable indicating the baseline ($X_{ti}$=0) or postbaseline period ($X_{ti}$=1), $Z_i$ is an indicator for group (1=control, 0=intervention), $tX_{ti}$, $tZ_i$, $Z_iX_{ti}$ and $tZ_iX_t$ are interactions of the respective variables, $u_{0i}$, $u_{1i}t$ and $e_{ti}$ are respectively the between and within home error terms.
†Trajectory defined as the estimated PEs over time.

### *Sensitivity analyses*

To test the robustness of results, linear mixed effects models were also analysed for: (a) the subset of data points that omit 138 outliers having an Anscombe residual ≥3 standard deviations from the mean[62]; (b) the subset of homes having at least 7 days of PE data in both baseline and postbaseline (n=280). Results for these subsets were not appreciably different from results in table 2.

### Air nicotine and reported behaviour results

GEE analyses revealed a significant group by time effect on several variables (table 3). A statistically significant greater decrease in geometric mean levels was found in the intervention group than in the control group for air nicotine concentration (−6.62%), cigarette smoking (−8.65%), e-cigarette use (−11.33%) and frying with oil (−17.97%). A near-significant greater decrease for marijuana smoking (−9.15%) was found (p=0.057). For burning food, there was a significantly greater *increase* (31.21%) in the intervention group. All significant effects held when analyses were limited to a consistent cohort (ie, homes that had non-missing results for a given measure at both pretest and post-test).

**Table 3** Pre-to-post change in air nicotine concentration and reported particle-generating behaviours by group

| Measure | Group | % Pretest-to-post-test change in geometric mean* | % change in time effect† relative to control* | P value‡ |
|---|---|---|---|---|
| Air nicotine§ | Control | −0.29 | Reference | |
| | Intervention | −6.89 | −6.62 | **0.002** |
| Cigarette¶ | Control | −0.42 | Reference | |
| | Intervention | −9.04 | −8.65 | **0.048** |
| E-cigarette¶ | Control | 2.51 | Reference | |
| | Intervention | −9.10 | −11.33 | **0.020** |
| Marijuana¶ | Control | −0.19 | Reference | |
| | Intervention | −9.32 | −9.15 | 0.057 |
| Incense/candle** | Control | −7.08 | Reference | |
| | Intervention | −17.16 | −10.84 | 0.288 |
| Fry with oil** | Control | 4.79 | Reference | |
| | Intervention | −14.04 | −17.97 | **0.014** |
| Vacuum/dust/sweep** | Control | 1.34 | Reference | |
| | Intervention | 3.19 | 1.83 | 0.775 |
| Burn food** | Control | −3.67 | Reference | |
| | Intervention | 26.39 | 31.21 | **<0.001** |

*Estimate from generalised estimating equations model.
†Time effect (for each group)=post-test geometric mean divided by pretest geometric mean.
‡Significance of the group-by-time interaction term.
§Concentration (μg/$m^3$).
¶Number smoked/used in past 7 days.
**Number of days during past 7 days that the activity was engaged in.

## DISCUSSION

### Summary of outcomes

The first published outcome study from our Project Fresh Air trial focused on mean indoor particle concentrations and found a 13.1% greater decrease in the geometric mean level of airborne particles in the experimental group versus controls, demonstrating the capacity of the intervention to improve overall air quality in homes with smokers and children.[49]

The current study focused on behaviours generating high concentrations of fine air particles in the home, and especially on behaviours that generate PEs. Both components of the intervention—alerts from the monitor, and coaching from staff that included presentation of historical charts of PEs over the past week—sought to reduce activities that triggered aversive lights and sounds. Thus, the outcome selected for analysis was based on the high-particle-level-generating behaviours on which we intervened by delivering coaching and immediate contingent consequences that were more consistent than intermittent coaching sessions.[52 63]

We observed two main intervention effects on PEs, both favouring the intervention group. First, there was a significantly greater reduction in PEs immediately after the intervention began. Second, there was a significantly faster decline in PEs over the course of the intervention period. Given the modest but consistent validation correlations of PEs with air nicotine and with reported measures of behaviours such as tobacco and marijuana smoking, as well as burning of incense or candles, we are confident that the observed decreases in PEs represented reductions in these particle-generating behaviours. Moreover, the differential group-by-time decrease in PE counts was paralleled by differential group-by-time decreases in air nicotine, cigarette smoking and e-cigarette use, which were larger in the intervention group, suggesting convergent validity.

Collectively, these results support the inference that indoor smoking—the primary behaviour targeted by the intervention—was reduced by real-time aversive lights and sounds presented on the occurrence of elevated particle concentrations along with coaching that emphasised moving smoking outside the home.

Our findings are ground-breaking because feedback on behaviours generating high particle levels was provided in real time, and our outcome measures were collected continuously over the entire duration of study participation. Previous studies have been limited by using *delayed* air particle level feedback employed only episodically.[37 38 40 41]

## Limitations

We installed, air nicotine dosimeters in homes only during the pretest and post-test weeks, sampling only subsets of the entire study timeframe on which PE outcome analyses were based.

Not all homes in the intervention condition received the intended intervention in full, due to missed coaching sessions or problems with the monitor alert feedback. Postbaseline data collection was attenuated due to loss to follow-up in both groups. Primary analyses therefore used the conservative intent-to-treat approach; sensitivity analyses corroborated results.

We presented aversive lights and sounds—mildly punitive consequences—contingent on behaviours that generated air particles, but a punishment strategy is typically not attractive to clinicians or their patients. Moreover, punishment can have undesired side effects, including counter-aggression.[64] During the intervention, a few families turned off or damaged the equipment, or called us to collect it. Despite our use of aversive consequences, and the inherent emotional distress caused by delaying a cigarette, such overt avoidance behaviour among intervention participants was remarkably infrequent.

Neither the real-time feedback nor the PE measure of behaviour distinguished the source of the particles, so we were unable to quantify the relative contributions to PE counts in the home made by various types of behaviours. However, given that the strongest association was with air nicotine, it appears our PE measure captured indoor tobacco smoking. Future intervention studies should make use of more specific measures that can pinpoint smoking or other types of behaviour, and should convey all feedback to participants in real time.

## Implications

Improvements in real-time monitoring specificity would enable the discrimination of sources. For example, currently available real-time nicotine monitors using state-of-the-art sensing technology and algorithms are able to more specifically detect tobacco smoke.[65] Miniaturisation of the monitor to make it wearable would enable estimates of particle/SHS exposure specific to individuals. Such refinements might make the device practical as part of preventive paediatric telemedicine or ongoing evaluation of the toxic environments of homes for patients under care.

This study offered precise use of principles of behaviour as applied to smoking. Lights and sounds punished smoking behaviour, and coaching sessions using Motivational Interviewing prompted parents to plan new ways of avoiding smoking in the home. By emphasising the participant's best ideas about what might help them avoid smoking in the home and also help them avoid aversive signals, we set the stage to socially reinforce novel and practical plans to avoid smoking in the home. Our results showed that principles of behaviour worked and did so under less than ideal conditions.

Additional research is needed to determine the effects on indoor smoking due solely to real-time contingencies of reinforcement and/or punishment. Future studies should test shaping procedures to gradually achieve reduction goals using reinforcing consequences instead of punishing consequences to shape behaviour that might be sustained. Theoretically, such shaping procedures would be more powerful and more acceptable to the smoker.[66] Micro-incentives, successfully used to increase walking,[67 68] should be tested as reinforcing consequences for smoking only outside the home and car.

New technology now offers opportunities to shape precise and subtle changes in behaviour by equipping homes with multiple real-time sensors having the capability to 'speak to the family', approximating real verbal interactions. Future trials should test such feedback for families with high-risk children and/or adults in order to test the degree to which vulnerable family members experience reduced severity of asthma or fewer potentially fatal outcomes (eg, myocardial infarction) relative to controls. This trial sets the stage for a series of new studies that may more effectively protect children and adults by strengthening the depth and breadth of machine-based contingencies for altering smoking behaviour.

## CONCLUSION

This study presents compelling evidence that providing participants with coaching and real-time mildly aversive feedback for events generating high air particle levels in their homes is effective at decreasing the frequency of smoking events, as well as other particle-generating events. Our results are promising for future control of smoke exposure among high-risk populations, such as exposed children living with smokers.

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### What this paper adds

- ► Indoor air particles, especially from tobacco, are known to be harmful.
- ► Particles, including tobacco smoke, are often generated by human behaviour.
- ► Brief, episodically delivered coaching interventions can change behaviour and improve air quality.
- ► Our study used episodic coaching and continuous real-time feedback, contingent on behaviour, that reduced indoor tobacco smoking and other particle-generating behaviours.

**Contributors** MFH, NEK, SCH, JB and PJEQ drafted the concept and design, aided in data interpretation, and assisted with drafting the manuscript, on which NEK and SCH served as equally contributing senior authors. BN, JB and SL handled data acquisition/management, conducted data analyses and helped draft the manuscript. VB conducted data analyses and helped draft the manuscript. MCB-D devised study protocols. MCB-D (during the first two years of the study) and SO (during the final two years of the study) coordinated field and office work, maintained operational fidelity and edited the manuscript. EJB edited the manuscript, providing pivotal feedback on content. WMO provided medical implications for future use of this type of technology, and edited the manuscript. DC performed laboratory analyses of air nicotine and urine cotinine samples. GEM edited the manuscript and contributed to the initial and final analytical models and their interpretation. RR provided leadership for the DSMB for the study, edited the manuscript and provided advice regarding the next steps in this line of research. CJ and JM provided access to and aided with recruitment of families in the Navy who qualified for the study, and confirmed possible future uses in the medical services provided by the Navy. MFH is guarantor. All authors approved the submitted manuscript.

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**Data sharing statement** After de-identification, data will be made available to applicants who agree to use the data only for scientific purposes. Availability of the data and contact information for interested applicants will be posted on our website (http://www.cbeachsdsu.org).

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