

Pollution exposure and health: The role of private actions and environmental externalities in Nairobi

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Abstract

Air pollution is responsible for around 8 million deaths each year. Many of the world's urban poor are exposed to both indoor air pollution—generated by their own use of biomass for cooking—and ambient air pollution—generated by transportation, industry, and other economic activity—yet these two major sources of pollution have thus far been studied almost entirely independently. If ambient air pollution dampens the health benefits from private technology adoption, then meaningful health improvements will require government intervention addressing negative externalities through environmental regulation. We conduct a field experiment studying the impacts of three years of improved cookstove usage on 1,000 biomass cookstove users in Nairobi, Kenya. We collect detailed personal, high-frequency PM1.0, PM2.5, and CO concentrations and extensive quantitative and self-reported health measurements. 10-minute peak PM2.5 exposure increases by $94\mu\text{g}/\text{m}^3$ during cooking for the control group, but improved stove ownership reduces this by $32\mu\text{g}/\text{m}^3$ (34%). This drives a sizeable 0.22 standard deviation reduction in self-reported health symptoms and USD 1.50 (39%) in weekly energy savings. However, these peak pollution reductions are overshadowed by ambient pollution of $35\mu\text{g}/\text{m}^3$. As a result, they have negligible impacts on average air pollution exposure, and we can rule out meaningful improvements in blood pressure, blood oxygen, and a wide array of self-reported diagnoses. In the presence of high ambient pollution, private fuel switching will not generate large improvements in aggregate pollution exposure or chronic health.

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1 Introduction

According to the World Health Organization (WHO 2021) air pollution is “the single biggest environmental threat to human health;” it is responsible for 7–9 million premature deaths annually (10-15% of all deaths; Lancet 2017). 92% of those deaths occurred in low- and middle-income countries (LMICs). The 2 billion people who live in LMIC cities are exposed to two distinct sources of air pollution. Household-generated air pollution (HAP) is generated by household activities such as cooking. Ambient air pollution (AAP) is generated by economic agents other than the household, primarily through economic activities such as transportation, energy generation, or production.

We conduct a randomized field study in Nairobi, Kenya to estimate the causal impact of improved cooking technologies on health in an urban context. We randomly assign credit and subsidies for cookstoves to enable causal inference and conduct follow-up surveys 3–4 years after adoption. To measure respondent-level pollution exposure, each respondent wears a backpack containing two air pollution monitoring devices that record particulate matter at below 1.0 or $2.5\mu m$ in diameter (PM1.0 and PM2.5, respectively) and parts-per-million of carbon monoxide (CO ppm) on a minute-by-minute basis for 48 hours. A complementary time use survey records the indoor or outdoor activities each respondent engaged in during each of those 48 hours. To measure health, we complement detailed self-reports on health symptoms and diagnoses with quantitative measurements of systolic and diastolic blood pressure, blood oximetry, anthropometrics, and child development. We use a set of cognitive exercises to measure attention, working memory, and response inhibition, and finally, a socio-economic survey to understand impacts on economic well-being.

This paper advances our understanding of how air pollution affects human health in three ways. First, there is extremely little causal evidence on the health impacts of improved stove adoption using quantitative measures of both air pollution and health, despite the global scale of the problem (the RESPIRE trial in rural Guatemala being an important exception; Smith-Sivertsen et al., 2009). Second, almost all papers that causally estimate the impacts of air pollution on health use data on average concentrations (see for example Chay and Greenstone, 2003; Clay et al., 2022; Currie and Walker, 2011; Deryugina et al., 2019; Ebenstein et al., 2017; Greenstone and Hanna, 2014; Isen et al., 2017; Schlenker and Walker, 2015), whereas we use high-frequency pollution monitoring to evaluate the importance other moments of pollution exposure, including most notably short-duration peaks. Third, papers studying air pollution almost exclusively study either HAP or AAP, whereas our paper studies both simultaneously, allowing us to examine their relative impacts on environmental health for the billions who live in urban poverty. This has important policy implications, as HAP requires removing private barriers to adoption while AAP requires regulation of environmental externalities.

The analyses generate three key findings. First, treatment persists: 83% (90%) of respondents who did (not) purchase a Jikokoa still (do not) own one more than three years later. Improved cookstove users who still reside in urban areas continue to spend USD 1.49 per week less on charcoal (USD 77 per year), 39% less than the control group (similar to Berkouwer and Dean, 2022a).¹

¹In rural areas, where many favor gathering free firewood, the 39% reduction corresponds to USD 0.71 per week.

Second, the modern stove reduces peak cooking emissions by 34%. Specifically, for the control group, peak emissions while cooking are $94\mu g/m^3$ higher than their median exposure, but modern stove ownership reduces this by $32\mu g/m^3$.² This can explain a statistically significant 0.23SD reduction in an index of self-reported respiratory symptoms such as sore throat, headache, cough, and runny nose. An analysis of the mechanisms confirms that these respiratory symptoms are correlated with peak levels and not with average concentrations.

Third, due to the short-lived nature of the reductions in cooking emissions, and a context of high background exposure—averaging $25\mu g/m^3$ when not cooking—these large reductions in cooking pollution have negligible impacts on aggregate air pollution exposure ($\hat{\beta} = -2$, 95% CI: [-7.9, 3.9]). This departs from some earlier research asserting that HAP plays a dominant role in aggregate pollution exposure (see for example WHO 2014 and Fisher et al., 2021). These limited aggregate impacts can explain why we see no impacts on an array of health measurements (including blood pressure and blood oxygen), medical diagnoses (including pneumonia), or health-related expenditures. While improved stove adoption generates large reductions in smoke emissions, these changes have negligible pollution or health benefits against a backdrop of high AAP.

These findings have several important implications. First, research conducted using only average concentrations can miss important dimensions of pollution exposure, including some that may have significant health implications. Second, the lack of impact on average levels—and, perhaps as a result, the lack of impacts on quantitative or chronic health outcomes—indicates that private actions alone can only marginally improve the environmental health of the urban poor. Larger improvements will require government regulation of large negative externalities from the economic activities that generate AAP.

Many of the leading papers studying AAP quantify the impact of average concentrations on mortality and morbidity use highly aggregated data (in addition to those mentioned above, examples include Hanna and Oliva, 2015a; Simeonova et al., 2019). This mimics EPA regulations, which generally target 365-day averages or 24-hour averages for PM2.5. While a number of excellent papers document concavity in the dose-response function (see for example Gong et al., 2023; He et al., 2016; La Nauze and Severnini, 2021), this literature generally uses average concentrations rather than examining non-linearity in regards to within-day extremes.

The HAP literature has associated a wide range of health problems with energy-intensive cook-stove usage (Lee et al. (2020) and Thakur et al. (2018) provide reviews), and the transition towards cleaner cooking technologies has been subject to tremendous policy debate (Gill-Wiehl and Kammen, 2022). However, the existing evidence on health improvements from improved cooking technologies suffers from three key shortcomings. First, the evidence is still primarily correlational rather than causal. Lee et al. (2020) find that only 6 of 437 studies examining the impacts of stoves on pollution and health are randomized trials. Gordon et al. (2014) discuss in the Lancet the “urgent need for clinical trials evaluating cleaner fuel interventions on health outcomes.” Second, many RCTs lack

²For context, the U.S. Environmental Protection Agency (EPA) considers $>35\mu g/m^3$ (> 100 AQI) to be ‘unhealthy for sensitive groups’, $>55\mu g/m^3$ (> 150 AQI) ‘unhealthy’, and $>150\mu g/m^3$ (> 200 AQI) ‘very unhealthy’ (EPA, 2018).

quantitative pollution and health measurements; most rely on self-reported health outcomes. Only 24 of the 437 papers reviewed by Lee et al. (2020) measure personal pollution exposure concentrations, with many of the RCTs instead focusing on adoption rather than impacts.^{3,4} A notable exception to these first two limitations is a large-scale RCT conducted in a poor, rural community in Guatemala in 2002–2005 (RESPIRE; see McCracken et al., 2007; Smith et al., 2011; Smith-Sivertsen et al., 2009).

The third concern is that—like the RESPIRE trial—the existing research is overwhelmingly rural, despite the fact that two billion people will live in slums in Africa and Asia by 2050. In African cities, more than 80 percent of households rely on charcoal for daily cooking and heating needs (FAO 2017). In their review article, Thakur et al. (2018) identify no urban papers; we identify one more recent urban RCT that rigorously examines peak and duration of exposure to measure the pollution and health impacts of improved stove adoption (Alexander et al., 2018). However, their sample is restricted to pregnant women, the authors do not measure ambient concentrations, and they examine relatively modest variation in air pollution (a 5% and 13% reduction in peak emissions during the dry and rainy seasons, respectively, with no impact on mean PM2.5 or high exposure duration). Due to the lack of urban studies on HAP, and the fact that AAP highest in cities, there is effectively no evidence bridging the AAP and HAP literatures. Cities in low- and middle-income countries (LMICs) suffer disproportionately from both AAP and HAP. The 80% of the global urban population living in LMICs experience unhealthy PM2.5 levels on a daily basis (WHO 2021), partly due to limited environmental regulation and enforcement (Fisher et al., 2021; Greenstone and Jack, 2015). Many papers on AAP focus on higher-income countries, and those that study AAP in LMICs often do not simultaneously measure HAP. Katoto et al. (2019) find that many of the 60 AAP studies conducted in Sub-Saharan Africa either do not assess health effects or use limited direct measurements of air pollutants.

Finally, while a nascent literature documents the cognitive impact of air pollution (Archsmith et al., 2018; Ebenstein et al., 2016; La Nauze and Severnini, 2021; Sanders, 2012), little has been conducted in LMICs. Fisher et al. (2021) “identified 22 studies that quantitatively examined relationships between air pollution and IQ loss in children. None ... were done in African children.”

2 Background: Cookstoves and pollution among the urban poor

Traditional charcoal cookstoves produce indoor air pollution that causes millions of deaths each year (WHO 2017; Bailis et al., 2015; Pattanayak et al., 2019). More than 4 billion people still do not have access to modern cooking methods (WB 2020). 67–70 percent of the 12 million households in Kenya rely on biomass (wood and charcoal) as their primary household fuel (KNBS 2019; WB 2019). Around 42 percent of Kenyan households use a Kenyan ceramic ‘*jiko*’ for daily cooking, with

³See for example Bensch et al. (2015), Bensch and Peters (2019), Burwen and Levine (2012), Chowdhury et al. (2019), Levine et al. (2018), Miller and Mobarak (2013), Mobarak et al. (2012), and Pattanayak et al. (2019).

⁴Another common concern is lack of stove usage (see for example Beltramo and Levine (2013) and Hanna et al. (2016)). Berkouwer and Dean (2022a) rule this out in this paper’s study context.

the primary alternatives being wood stoves (in rural areas) and liquefied petroleum gas (LPG) and kerosene stoves (in urban areas) (Ministry of Energy, 2019). All of this study’s participants resided in Nairobi at baseline, and their primary energy-using durable at baseline was a *jiko*. According to the World Bank’s Kenya Country Environmental Analysis (2019), “Those who cook inside with poor ventilation have $400\text{--}600 \mu\text{g}/\text{m}^3$ average annual concentration of PM_{2.5} in their household.” These levels are extremely high: the WHO 2021 defines its ‘healthy’ threshold to be $5\mu\text{g}/\text{m}^3$.

2.1 The energy efficient Jikokoa cookstove

Figure 1 displays a *jiko* as well as the Jikokoa, an energy efficient charcoal stove produced by Burn Manufacturing (‘Burn’). Burn began producing stoves in Nairobi in 2014 and has now sold more than two million energy efficient cookstoves. Berkouwer and Dean (2022a) provides more detail on charcoal consumption, barriers to adoption, and access to credit among potential adopters in Nairobi.

Figure 1: Traditional *jiko* (‘stove’) and energy efficient stove



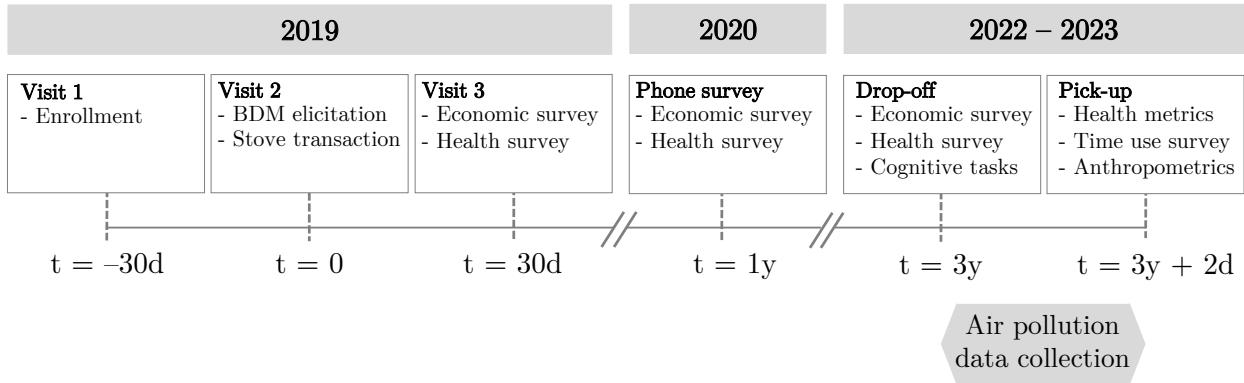
Reproduced from Berkouwer and Dean (2022a). On the left is the traditional *jiko*. On the right is the energy efficient stove. The two stoves use the same type of charcoal and the same process for cooking food, hence the energy efficient stove requires essentially no learning to adopt. After usage, the user disposes of the ash using the tray at the bottom. The central chamber of the energy efficient stove is constructed using insulating materials.

The primary difference between the Jikokoa and the *jiko* is that the Jikokoa’s main charcoal combustion chamber is constructed using improved insulation material and designed for optimized fuel-air mixing. It is made of a metal alloy that better withstands heat, and a layer of ceramic wool insulates the chamber to cut heat loss. To maximize the charcoal-to-heat conversion rate, parts are made to strict specifications, and components fit tightly to minimize air leakage. These features were designed and tested by laboratories in Nairobi and Berkeley. In line with lab estimates, Berkouwer and Dean (2022a) find that adoption of the Jikokoa reduces charcoal usage (as measured through charcoal expenditures and ash generation) by 39%. Adoption of the energy efficient stove does not require any behavioral adaptation or learning. The cooking processes are identical. Most adopters continue cooking the same types and quantities of food as before, using the same type of charcoal.

3 Study design and methodology

The study consists of baseline and short-term follow-up activities conducted in 2019, a medium-term follow-up conducted in 2020, and a long-term follow-up conducted in 2022–2023. [Figure 2](#) presents an overview of the study elements included in each survey round.

Figure 2: Timeline of field activities



Participants who adopted the stove did so during Visit 2 ($t = 0$). For 89% of respondents the long-term endline was conducted between 3.4–3.7 years after Visit 2. Due to COVID-19 related health restrictions, the 2020 follow-up survey was conducted over the phone.

In the initial baseline enrolment survey activity conducted in April–May 2019, enumerators enrolled respondents residing in urban settlement areas around Nairobi, Kenya who used a traditional charcoal stove as their primary daily cooking technology and who spent at least USD 3 per week buying charcoal. Within each household they enrolled the primary cookstove user. To elicit baseline levels of health, enumerators asked respondents whether they had experienced a persistent cough or breathlessness in the past week. If they had any children under 16 who lived with them, we asked the same about the child(ren). Enumerators then elicited respondent beliefs about the potential health impacts of an improved stove in several ways, using methodologies from the cookstove health literature (Hooper et al., [2018](#); Usmani et al., [2017](#)). Specifically, in an unprompted manner they asked respondents what they perceived to be the main benefits of the improved stove—62 percent stated ‘reduced smoke’ (95 percent said ‘saving money’). They then asked several Likert scale questions about the extent to which the respondent thought usage of a traditional stove has had negative impacts on their health, and how much adoption of an energy efficient stove might improve their health.

The main visit—Visit 2, completed by 955 respondents—took place approximately one month after each respondent’s baseline visit. During this visit, respondents received at least a USD 10 subsidy off the Jikokoa retail price and were able to buy the stove using the subsidy. Of the 955 respondents who completed the main visit, 570 (60 percent) adopted the Jikokoa stove.

In July–August 2019, approximately one month after the main visit, enumerators conducted a short-term endline survey. In 2020, enumerators conducted a medium-term phone survey.⁵ These

⁵Due to COVID-19, all surveys conducted in 2020 were conducted over the phone.

Table 1: Summary statistics from respondent surveys

| | N | Mean | SD | 25 th | 50 th | 75 th |
|---|-----|--------|------|------------------|------------------|------------------|
| Female respondent | 702 | 0.96 | | | | |
| Completed primary education | 702 | 0.70 | | | | |
| Completed secondary education | 702 | 0.26 | | | | |
| Age | 702 | 41.46 | 11.8 | 33.0 | 40.0 | 48.0 |
| Children under 5 in home | 702 | 0.50 | 0.7 | 0.0 | 0.0 | 1.0 |
| Daily earnings (USD) | 563 | 2.77 | 5.8 | 1.0 | 1.7 | 3.1 |
| Daily charcoal expenditure (USD) | 702 | 0.48 | 0.6 | 0.2 | 0.3 | 0.6 |
| Minutes spent cooking per day | 702 | 127.54 | 59.5 | 90.0 | 120.0 | 150.0 |
| ... of which indoor | 702 | 111.80 | 61.3 | 70.0 | 109.0 | 150.0 |
| Owns Jikokoa | 702 | 0.52 | | | | |
| Owns traditional wood or charcoal jiko | 702 | 0.57 | | | | |
| Owns LPG stove | 702 | 0.59 | | | | |
| Owns electric stove | 702 | 0.01 | | | | |
| Mostly uses modern stove | 702 | 0.53 | | | | |
| Blood oxygen | 696 | 96.74 | 2.4 | 96.0 | 97.0 | 98.0 |
| Average systolic blood pressure | 696 | 123.46 | 22.0 | 108.3 | 118.5 | 131.7 |
| Average diastolic blood pressure | 696 | 81.75 | 12.9 | 73.0 | 79.3 | 89.0 |
| Number of health symptoms | 702 | 2.47 | 2.6 | 0.0 | 2.0 | 4.0 |
| <i>In the past month, have you experienced...</i> | | | | | | |
| Fever | 702 | 0.22 | | | | |
| Headache | 702 | 0.48 | | | | |
| Persistent cough | 702 | 0.23 | | | | |
| Runny nose | 702 | 0.22 | | | | |
| Sore throat | 702 | 0.15 | | | | |
| Always feeling tired | 702 | 0.28 | | | | |

Standard deviation and 25th, 50th, 75th reported for all non-binary variables. Blood pressure is averaged over three readings taken consecutively.

surveys ask about a range of socioeconomic outcomes, including charcoal expenditures, savings (in bank accounts, mobile money accounts, or rotating savings groups), as well as the same health symptoms questions asked during the baseline surveys.

In 2022-2023 enumerators conducted a long-term survey round. Table 1 presents summary statistics collected during these surveys. Enumerators were able to reach 775 of the 942 respondents they attempted to reach, and successfully surveyed 702.⁶ 95% of respondents were surveyed between

⁶13 of the 955 respondents completed the main visit in 2019 but removed themselves from the study between 2019 and 2022. 167 respondents could not be contacted in 2022-2023 despite repeated phone calls to their phone numbers or any other phone numbers they had used for earlier SMS surveys or MPESA payments. Physical attempts to track individuals residing in the study areas were hampered by the recent demolitions of housing in Nairobi's settlement areas (The Star, 2023). Respondents who were contacted but who did not complete a 2022-2023 survey did not do so for various reasons, including nonconsent, migration, physical incapacitation, or death. Attrition is balanced by treatment assignment, take-up, and baseline health (Table A13).

3.4–3.7 years after the original main visit.

The long-term survey round consisted of two surveys, the second approximately 48 hours after the first. The surveys were designed to take quantitative measurements of three long-term outcomes: air pollution, physical health, and cognition. The accompanying socioeconomic survey included questions on charcoal expenditures, Jikokoa ownership and usage, other cooking technology ownership, maintenance, food cooked, home heating, in-network Jikokoa purchases, savings, income, and work activities.

To match high-frequency pollution data to specific activities, the second survey included a time use module inquiring about which activities the respondent was engaged in for each hour between the two surveys, whether they were indoors or outdoors during that hour, and if they were cooking, which stove(s) they were using. Most respondents cook primarily between the morning hours of 5–8am and the evening hours of 6–9pm.⁷

3.1 Causal identification

After completing the initial baseline enrolment survey, each respondent was randomly assigned a subsidy of between USD 10–39 for the energy efficient Jikokoa stove, which cost USD 40 in stores at the time. The random assignment of subsidies was stratified on baseline charcoal usage. The subsidy assignment was cross-randomized with a random credit treatment allowing recipients to pay for the stove in installments over a 3-month period, as well as an attention treatment designed to increase the salience of long-term charcoal savings.

During visit 2, enumerators used a Becker-DeGroot-Marschak (BDM) mechanism (Becker et al., 1964) with a guided binary search to elicit WTP for the Jikokoa stove. Respondents whose WTP was at least as high as their randomly assigned price (the store price of USD 40 minus the randomly assigned subsidy) then adopted the stove.⁸

The credit treatment doubled WTP (95% CI: 93%–114% increase) while the attention treatment had no effect on WTP (Figure A3 shows the full distributions of WTP by treatment group). The randomized credit and subsidy treatments were highly predictive of improved stove adoption: among those in both the high subsidy and the credit treatment group 93% adopted the Jikokoa, whereas among those in both the low subsidy and the credit control group only 8% did. To estimate the causal effect of improved stove adoption on long-term outcomes we use the randomly assigned subsidy, the credit treatment assignment, and their interaction as instruments for adoption. We report weak instrument F-statistics where relevant—the first stage is generally strong.

Using the randomly assigned subsidy as an instrument, Berkouwer and Dean (2022a) find that adoption of the Jikokoa causes a 39% reduction in charcoal usage, generating \$120 in fuel savings per year—approximately one month of average respondent income.

⁷There are modest differences in the types of technologies used during different types of day, with LPG used more in the mornings and a charcoal jiko or Jikokoa used more in the evenings (Figure A5). Anecdotally, this is due to a preference for a fast-lighting stove (which the LPG stove is, in comparison to biomass) in the morning, for a small meal or hot beverage, and a longer-cooking stove when preparing larger meals.

⁸98.6% of respondents who ‘won’ the stove through the BDM actually adopted the stove.

3.2 Air pollution exposure concentrations

We measure particulate matter (PM1.0 and PM2.5) and carbon monoxide (CO ppm). The PM monitor is a Purple Air II Air Quality Sensor (PA-II) that takes one measurement per minute (Panel A of [Figure A4](#)).⁹ The CO monitor is a Lascar EL-USB-CO Carbon Monoxide Data Logger that takes one measurement every two minutes (Panel B of [Figure A4](#)).¹⁰ To confirm device accuracy and precision, a test of co-located readings reveals devices are strongly correlated with a small and generally stable gap between some devices ([Figure A1](#)). For this reason we include device fixed effects in all regressions.¹¹

Following best practices (Gordon et al., 2014; Gould et al., 2022), we designed the deployment methodology to collect exposure as experienced by respondents rather than stationary monitoring of kitchen concentrations. To achieve this, we used procedures developed by the Berkeley Air Monitoring Group (Johnson et al., 2021). During the first endline survey we provided each respondent with a small mesh backpack containing the two devices (Panels C and D of [Figure A4](#)). 48 hours later the enumerators then picked up the devices, downloaded the data, recharged the 48-hour battery pack, and placed them in a new backpack before re-deploying it with a different respondent.¹² Respondents were asked to wear this backpack continuously whenever feasible, or to keep it within one meter, at waist level, when wearing it was infeasible. We did not quantitatively monitor backpack wearing, as this would have required installing GPS trackers on the backpacks which we felt violated participants' privacy. However, qualitatively, enumerators reported generally high backpack wearing.¹³ Our methodology is in line with best practices from the air pollution monitoring literature (Burrowes et al., 2020; Chillrud et al., 2021; Gould et al., 2023).

[Figure 3](#) maps respondents across Nairobi according to their average air pollution exposure. Collecting pollution exposure over a 48-hour period captures HAP as well as AAP generated by industrial facilities, traffic, or other sources in urban Nairobi. Pope et al. (2018) for example document that average PM2.5 and PM1.0 in Kenya are on average 2.8 times higher in urban roadside locations than in rural locations.

Panel A of [Figure 4](#) presents average pollution by whether or not the respondent owned a Jikokoa stove as of the 2022–2023 surveys over the hours of the day. The levels and diurnal patterns of PM2.5

⁹We average the PA-II *a* and *b* readings, and top-code data at $419\mu\text{g}/\text{m}^3$ above which the device saturates. We apply the PAII calibration methodology from Giordano et al. (2021) and Ward et al. (2021) to correct for humidity and local air composition. Building on Tryner et al. (2020), if the difference between the *a* and *b* readings is at least 25% and at least $15\mu\text{g}/\text{m}^3$ the reading is removed from the sample (1.7% of readings).

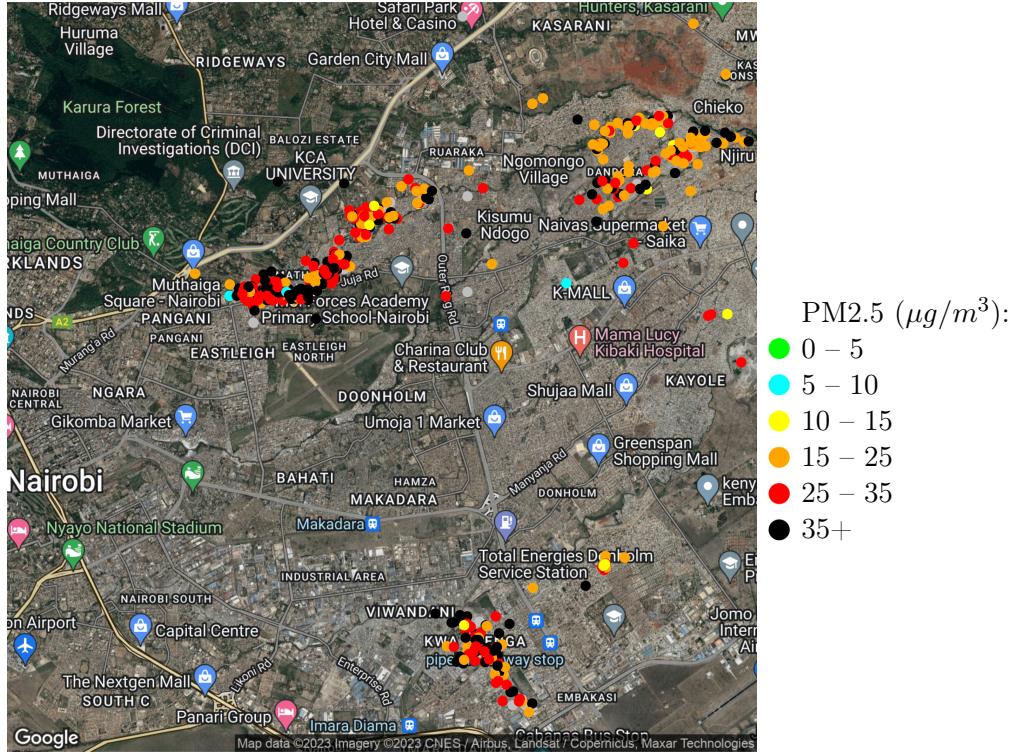
¹⁰Each CO monitor has an independent calibration factor. Monitors were re-calibrated every two months, between survey breaks. We include monitor fixed effects in all regressions.

¹¹Including an interaction between device fixed effects and a linear time trends could account for heterogeneous trends across devices. Doing so introduces noise and therefore increases standard errors, but does not qualitatively change the results.

¹²85% of respondents held the device between 45–50 hours. Air pollution data is missing for 45 respondents who only had time to complete a single survey.

¹³Around halfway through surveying, enumerators raised concerns about a lack of continuous backpack wearing. We paused surveying activities and discussed the issue with enumerators. It turns out that the issue was that respondents would take off the backpack for example while sleeping it (placing it next to their beds) or while working statically (placing it

Figure 3: Average air pollution (PM 2.5) for participants by their home locations



Distribution of respondents across Nairobi. Colors correspond to average particulate matter (PM 2.5) exposure. Respondents for whom pollution was not recorded are shown in gray. The WHO air quality guideline (AQG) is $5\mu\text{g}/\text{m}^3$ (WHO 2021). WHO interim targets 1 through 4 correspond to 10 , 15 , 25 , and $35\mu\text{g}/\text{m}^3$. Some respondents were surveyed outside the visible area.

and PM1.0 follow the air pollution patterns documented by Pope et al. (2018) in urban Kenya. We do not observe any meaningful seasonal heterogeneity in air pollution.

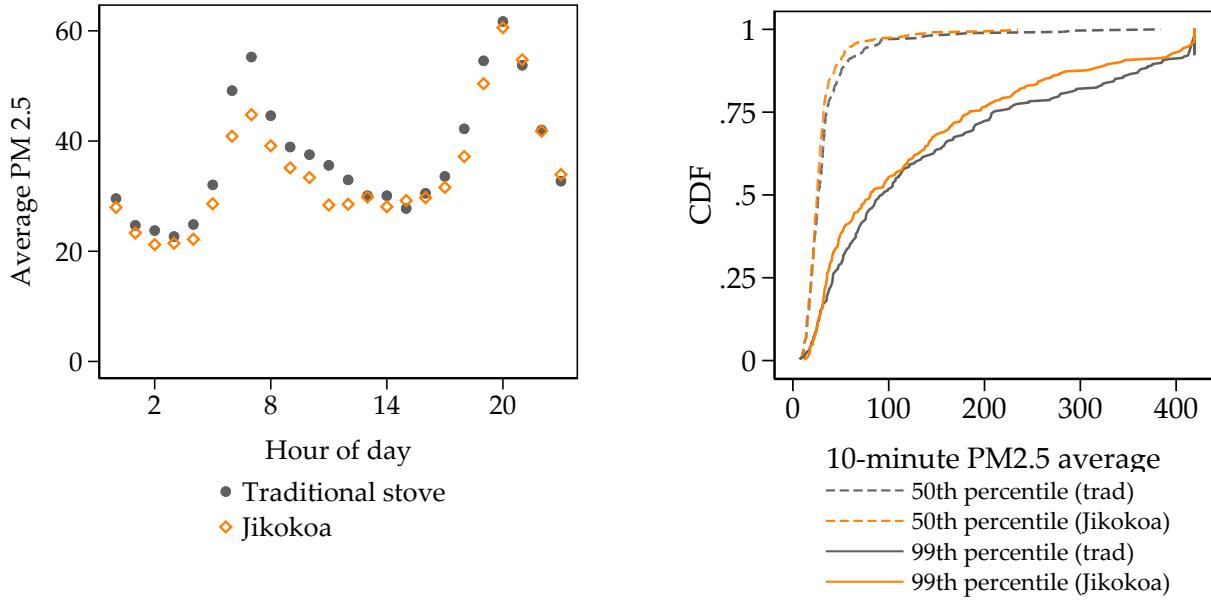
Panel B of Figure 4 shows the cumulative distributions of each respondent’s 50th (median) and 99th percentile 10-minute average, with the 99th percentile 10-minute average representing approximately the worst 15 minutes of one’s day. For 89% of respondents, their median 10-minute average is below $50\mu\text{g}/\text{m}^3$. However, for most respondents, the worst 15 minutes of their day is well above $84\mu\text{g}/\text{m}^3$ —in fact, this exceeds $200\mu\text{g}/\text{m}^3$ for 23% of respondents.

Matching hourly time use data and hourly pollution data indicates that PM2.5 is lowest when sleeping ($29.7\mu\text{g}/\text{m}^3$) and highest when cooking or eating ($39.2\mu\text{g}/\text{m}^3$) on average (Table A1).

3.3 Physical health

Enumerators record systolic and diastolic blood pressures using a sphygmomanometer, following the procedures set by the CDC NHANES (2019). Respondents are asked to sit still, upright, and not engage in affecting behaviors (cooking, smoking, etc.) in the 30 minutes prior to the blood pressure readings. In line with guidelines, blood pressure is recorded three times and the analysis uses the average of the three readings. In the analyses we employ direct measures of systolic and

Figure 4: Particulate matter (PM2.5, in $\mu\text{g}/\text{m}^3$) pollution by Jikokoa ownership
 A) Over the hours of the day B) Distributions of 50th and 99th percentiles
 of 10-minute averages (by household)



diastolic blood pressure as well as indicators for having hypotension (low blood pressure, defined as $<90/60 \text{ mmHg}$), stage 1 hypertension ($130-139/80-89 \text{ mmHg}$), and stage 2 hypertension ($\geq 140/\geq 90 \text{ mmHg}$), as defined by the American Heart Association and the American College of Cardiology (Goetsch et al., 2021).

Enumerators use pulse oximeters (blood oxygen saturation monitors) to record haemoglobin oxygen saturation. Oximetry readings have been recently found to be a cost-effective approach to screening for respiratory infections (Floyd et al., 2015; National Library of Medicine, 2021; Van Son and Eti, 2021).¹⁴

The survey furthermore asks a large set of health questions. This includes a set of 10 yes/no questions asking if a medical professional had diagnosed the respondent with any medical diagnoses (including asthma, pneumonia, or other lung disease) and a set of 29 yes/no questions asking if the respondent experienced specific symptoms in the past 4 weeks (including fever, persistent cough, stomach pain, or rapid weight loss). The survey also asks about perceptions of health impacts, and frequency and financial costs of hospital visits. For female respondents, the enumerator also inquired about recent pregnancies, birth outcomes, and any recent newborns' weight and length. We use these self-reports to generate a standardized adult physical health index.

For children aged 5 and under, who are more likely than older children to spend more of their

¹⁴While we considered collecting spirometry or peak expiratory flow data, discussions with medical consultants in Kenya and the U.S. suggested that these run the risk of generating noisy and unusable data. We therefore chose to focus on improving the quality of the personal exposure, blood pressure, and blood oxygen measurements.

days with the primary cookstove user, frequent exposure to cooking-associated pollution may have negative health impacts. For each child under 5 who lives in the home the survey therefore asks about overall health, basic health symptoms (fever, vomiting, cough, etc.), school attendance, medical diagnoses. Using the UNICEF MICS6 (2020) methodology, the survey asked the relevant questions required to make an attempted pneumonia diagnosis. We again use these measures to generate a standardized child physical health index. The enumerator finally measured child and adult height, weight, and arm circumference as indicators for physical child development and for parental controls, respectively.

[Table 1](#) presents summary statistics on health outcomes. 18% of respondents report ever having been diagnosed with pneumonia, including 12% who had been diagnosed in the past three years.

3.4 Cognition

To provide an assessment of basic adult and child cognitive functions, we use three instruments. First, we use the Reverse Corsi Block task to measure working memory (Brunetti et al., 2014). Second, we use Hearts and Flowers to measure response inhibition (Davidson et al., 2006). Third, we use the d2 task for sustained attention (Bates and Lemay Jr., 2004; Brickenkamp and Zillmer, 1998). For detail on these cognitive assessments, see [Appendix C](#).

For the analysis we generate an adult cognitive ability index by standardizing each component to have a mean of 0 and a standard deviation of 1 and then taking the average across the outcomes, as well as a child cognitive ability index by standardizing each component to have a mean of 0 and a standard deviation of 1 and then taking the average across the outcomes.

4 Causal impacts

To estimate the causal effect of adoption of the energy efficient charcoal cookstove on health outcomes, we employ an instrumental variables approach where we use the randomly assigned BDM price (P_i), the randomly assigned credit treatment status (C_i), and their interaction (P_iC_i) as instruments for stove ownership d_i . These were the two random treatments found to have a statistically and economically large effect on stove adoption in Berkouwer and Dean (2022a).¹⁵ Since P_i and C_i are both randomly assigned, this regression identifies the causal effect of stove adoption on the outcomes of interest. Econometrically, this proceeds as follows:

$$y_i = \beta_0 + \beta_1[\hat{d}_i \sim P_i, C_i, P_iC_i] + \beta_2 X_i + \epsilon_i \quad (1)$$

where \hat{d}_i is a dummy for (endogenous) adoption. X_i is a vector of controls consisting of household baseline charcoal spending, savings, income, risk aversion, credit constraints, education, baseline self-reported health status, household adults and children, and a geographic neighborhood indicator assigned using a K-means clustering algorithm. The outcome variable y_i varies across regressions.

¹⁵We omit a third random treatment, attention to energy savings, as it had no impact on adoption.

Note that \hat{d}_i could represent either initial adoption in 2019, or ownership status as of the 2022–2023 endline survey. Using initial adoption represents the longer-term effects of adoption, factoring in potential breakage or other subsequent changes in stove ownership, but underestimates contemporaneous effects as some treated individuals are no longer benefiting from the treatment. Long-term adoption status better estimates contemporaneous differences, but could result in an overestimated IV coefficient if changes experienced by respondents who initially adopted the stove but no longer own one at endline are attributed to the (smaller) treatment group. We present both estimates where relevant but use ownership as of the long-term follow up in most regressions.

4.1 Impacts of random treatments on stove ownership

Panel (A) of [Table 2](#) shows the causal impact of 2019 Jikokoa adoption on long-term ownership of the Jikokoa and other stove types. 90% of respondents who did not adopt a Jikokoa during the main visit also do not own one during the long term endline, and 83% of respondents who adopted a Jikokoa initially also own one three years later. This persistence generates a strong first-stage to study the impacts of the Jikokoa on other outcomes, with weak IV F-statistics between 20 and 50 depending on the specification ([Table A2](#) presents the first stage).

Jikokoa adoption does not appear to meaningfully increase adoption of other modern cooking technologies such as liquefied petroleum gas (LPG), bio-ethanol, or electric stove ownership, though we cannot rule out modest increases. We thus find limited evidence of the ‘energy ladder’ theory that initial adoption of an improved biomass stoves can act as a stepping stone towards even cleaner cooking technologies ([Hanna and Oliva, 2015b](#)), nor of the converse theory, that adoption of an intermediary technology can slow adoption of a more advanced technology ([Armitage, 2022](#)). The average household owns 1.9 unique stove types, indicating some degree of ‘fuel stacking’ (simultaneous ownership and/or use of cooking technologies that use multiple types of cooking fuel). LPG ownership has risen sharply in recent years, with 60% of respondents now owning an LPG stove, potentially as a result of a government LPG subsidy program ([IEA 2022](#)). The estimates take any stacking at face value, estimating the causal effect of improved cookstove adoption factoring in any continued use of existing stove (rather than an estimate of a strict switch from an existing stove to an improved stove).

Panel (B) of [Table 2](#) presents the impact of stove adoption on various socioeconomic outcomes. Column (2) uses 2022 Jikokoa ownership as the endogenous variable while Column (3) uses 2019 Jikokoa adoption as the endogenous variable. Improved cookstove ownership causes a USD 1.34 reduction in weekly charcoal expenditures, about a 30 percent reduction relative to the control group ([Table A6](#)). We split up the charcoal expenditure regression by whether the respondent still lives within 15 km of Nairobi city center (‘urban’) or whether they have moved outside of this area (‘rural’). Charcoal expenditures are more than twice as high among people residing in urban areas than those residing in rural areas.¹⁶ The treatment effect is driven by people living in urban areas,

¹⁶This is consistent with anecdotal and census evidence indicating that households living in rural areas are more likely to use firewood to cook as this can often be gathered at little to no cost.

Table 2: Primary socio-economic outcomes

| | Control Mean (1) | Treatment Effect (2022 Ownership) (2) | Treatment Effect (2019 Ownership) (3) | N |
|--|------------------------|---|---|-----|
| <i>Panel A</i> | | | | |
| Owns other wood or charcoal stove | 0.88 [0.33] | | -0.53*** (0.05) | 702 |
| Owns Jikokoa | 0.10 [0.31] | | 0.73*** (0.04) | 702 |
| Owns LPG stove | 0.57 [0.50] | | 0.04 (0.06) | 702 |
| Owns bio-ethanol stove | 0.15 [0.36] | | 0.01 (0.04) | 702 |
| Owns electric stove | 0.00 [0.06] | | 0.02 (0.01) | 702 |
| <i>Panel B</i> | | | | |
| Charcoal expenditures past 7 days (USD) | 3.65 [2.93] | -1.37*** (0.48) | -1.02*** (0.35) | 702 |
| Charcoal expenditures past 7 days (urban) | 3.80 [2.94] | -1.50*** (0.52) | -1.09*** (0.37) | 642 |
| Charcoal expenditures past 7 days (rural) | 1.79 [2.05] | 0.71 (1.09) | 0.80 (0.89) | 60 |
| Earnings past 2 weeks (USD) | 32.20 [35.31] | 7.24 (7.80) | 5.03 (5.36) | 563 |
| Total savings (USD) | 57.70 [94.87] | -3.83 (19.53) | -3.16 (14.26) | 701 |
| Has formal bank account (=1) | 0.12 [0.33] | 0.10 (0.07) | 0.07 (0.05) | 702 |
| Minutes cooking per day | 133.79 [57.29] | -2.56 (10.19) | -1.87 (7.46) | 702 |
| People in network who adopted Jikokoa | 0.75 [2.03] | 0.90** (0.41) | 0.66** (0.30) | 702 |

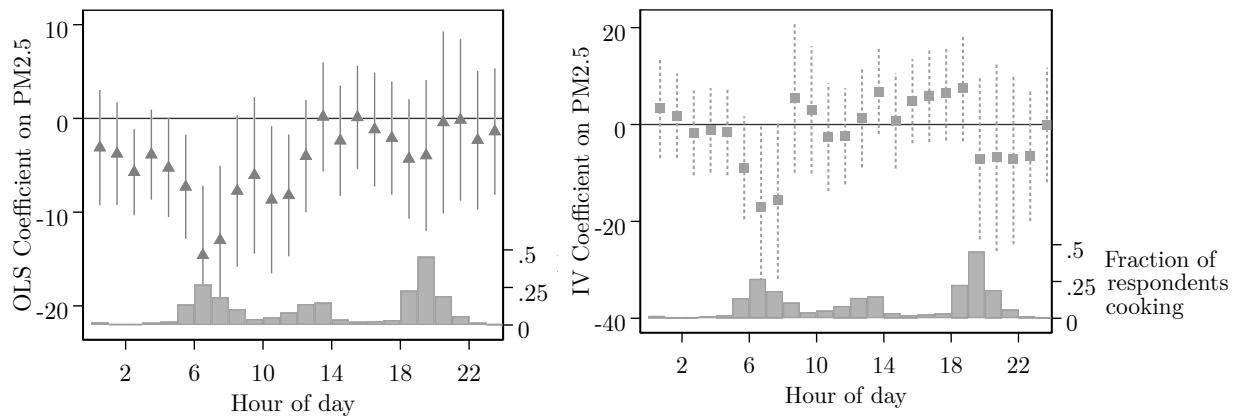
Panel A presents the causal impact of 2019 Jikokoa adoption on 2022–2023 cookstove ownership. Panel B presents the causal impact of Jikokoa ownership (as of 2022 or 2019) on outcomes recorded during the 2022–2023 endline surveys. All regressions use the randomly assigned price, credit treatment status, and their interaction as instruments for the (endogenous) cookstove adoption variables. Table A6 presents additional socio-economic outcomes relating to savings and in-network adoptions.

where improved stove adoption reduces charcoal expenditures by USD 1.48 per week on average. This adds up to approximately USD 77 per year for urban residents—statistically and economically a large result, though the estimate is slightly lower than short- and medium-term impacts (Berkouwer and Dean, 2022a).

In addition, Jikokoa adoption increases the propensity of individuals in an adopter’s network to adopt the stove. Specifically, it roughly doubles the number of Jikokoa stoves owned by members in a respondent’s network such as friends and family (see Table A6 for more detail), driven primarily by an increase in ownership by neighbors.

4.2 Impacts of stove ownership on air pollution

The link between stove ownership and air pollution varies significantly across hours in the day. Panel (A) of Figure 5 presents a standard OLS panel fixed effects regression, estimating a separate coefficient for each hour of the day. Panel (B) uses the instrumental variables approach to similarly estimate a separate causal estimate for each hour of the day. For comparability, both panels also present a histogram of the number of people who reported cooking during a given hour in the time use survey. Both graphs display three key characteristics. First, improved stove ownership reduces air pollution between 5–8am and between 8–10pm. Second, adoption does not appear to have caused any meaningful impact during any other hours of the day. Third, the timing of the reductions line up remarkably well with when respondents generally report to be cooking.



Panel (A) reports coefficients from an OLS regression of PM2.5 on Jikokoa ownership. Panel (B) reports coefficients from an equivalent IV regression, using subsidy, credit treatment status, and their interaction as instruments. In line with the regression results below, both regressions include week FE, device FE, and the interaction of and hour-of-day by day-of-week by neighborhood FE, as well as baseline demographic and socioeconomic controls. The gray bars report the fraction of respondents who report cooking during any given hour in the time use survey. [Table 3](#) presents regressions pooling hours 6–8am and 6–9pm which are the most common cooking hours, for PM2.5 (Panel A) and CO (Panel B).

Table 3 aggregates pollution exposure data for each individual and estimates the causal impact of stove adoption on three key moments of pollution exposure. Columns (1), (4), and (7) estimate the causal impact on mean exposure: average over the entire duration the respondent was with the device. Columns (2), (5), and (8) estimate the causal impact on the maximum average exposure experienced during a single clock hour. Finally, Columns (3), (6), and (9) estimate the causal impact on the 99th percentile of 10-minute intervals.

We furthermore separate impacts by whether the respondent was cooking or not, either as self-reported through the time use surveys (Columns (4)–(6)) or by limiting the data uniformly to 6–8am and 6–9pm (Columns (7)–(9)), as this is when most respondents report cooking (see Figure 5).

Two key patterns emerge. First, there is a large and statistically significant reduction of around (around 34% of the difference between control group cooking and non-cooking exposure) in the 99th

percentile of 10-minute means while cooking (Column 6). In other words, Jikokoa reduces the peak emissions from cooking by around 34% lower. Improved cookstove adoption also reduces the time spent cooking (Column (1) of [Table A5](#)); anecdotally this is driven by the fact that the improved stove takes less time to heat up. Thus, the reduction in pollution in maximum hourly average is even larger—49%—as this factors in both the reduced peak levels as well as a reduction in the time spent cooking in a certain hour (Column 5). These results approximately match the 37% reduction in charcoal expenditures identified in [Table 2](#): the reduction in charcoal usage approximately matches the reduction in PM2.5 exposure while cooking. These patterns are economically and statistically similar when the data are analyzed in logs ([Table A4](#)).

Second, however, despite these large reductions during cooking, there is only a very small reduction in aggregate average exposure, of around 6%, and it is not statistically significantly different from zero.¹⁷ The lack of impact on aggregate average air pollution can be reconciled with the relatively small amount of time spent cooking daily: respondents cook for 9% of the day (2 hours) on average. Indeed, the coefficient in Column (1) approximately corresponds to 9% of that reported in Column (4).

Table 3: Causal impact of cookstove adoption on pollution exposure
Panel A) All hours

| | PM2.5 | | | | CO | | | |
|--------------|---------------|---------------|------------------|-----------------|---------------|--------------|-----------------|----------------|
| | (1) Median | (2) Mean | (3) Max Hour | (4) 99th | (5) Median | (6) Mean | (7) Max Hour | (8) 99th |
| Own Jikokoa | 0.6 (1.9) | -2.0 (3.0) | -21.7* (12.9) | -22.7 (14.5) | -0.6 (0.5) | 1.8 (1.8) | 18.5 (13.5) | 20.8 (15.9) |
| Control Mean | 25.2 | 35.9 | 128.5 | 161.7 | 1.8 | 6.4 | 48.6 | 61.0 |

Panel B) When self-reporting cooking

| | PM2.5 | | | | CO | | | |
|--------------|---------------|------------------|-------------------|-------------------|---------------|--------------|-----------------|---------------|
| | (1) Median | (2) Mean | (3) Max Hour | (4) 99th | (5) Median | (6) Mean | (7) Max Hour | (8) 99th |
| Own Jikokoa | -5.2 (5.2) | -11.8** (5.7) | -26.3** (11.2) | -32.2** (15.5) | 0.1 (3.0) | 1.9 (4.1) | 9.2 (10.7) | 2.7 (15.0) |
| Control Mean | 34.4 | 45.2 | 78.2 | 119.0 | 5.0 | 10.6 | 27.8 | 42.7 |

Instrumental variables regression where the randomly assigned price, credit treatment status, and their interaction are used as instruments for endline Jikokoa ownership. All PM2.5 regressions have 590 observations and a Weak IV F-statistic of 48. All CO regressions have 607 observations and a Weak IV F-statistic of 49. Columns (1) and (5) use median exposure, (2) and (6) use mean exposure, (3) and (7) use maximum 1-hour average exposure, and (4) and (8) use 99th percentile of 10-min average exposure. Regressions include baseline demographic and socioeconomic controls and a fixed effect for the specific LASCAR or PA-II device used for that respondent. [Table A3](#) presents the same for when self-reporting not cooking and between 6–8am and 6–9pm specifically, which is less prone to recall bias. [Table A4](#) presents all four outcomes in logs. We omit presenting CO in log because 55% of 10-minute average observations and 37% of 1-hour average observations equal 0.

¹⁷ Assuming the true coefficient matches our estimate of -2.0, detect an effect at the 5% significance level would require a sample size of 4,975. Given the existing sample, the minimum detectable effect size is ± 5.8 .

Cooking hours are non-uniformly distributed across the day and may spuriously correlate with other diurnal patterns in pollution caused by economic activity. Using hourly data on self-reported cooking activity and pollution allows us to include hour-of-day fixed effects in the regressions. This regression is in some ways preferred as it accounts for diurnal patterns in pollution unrelated to cooking, however we lose significant variation since there is indeed significant correlation between hour of day and propensity to be cooking. While the IV estimates are noisier than the OLS estimates, the results present a similar story: cooking increases PM1.0 by $5.4\mu\text{g}/\text{m}^3$ and PM2.5 by $7.6\mu\text{g}/\text{m}^3$ relative to non-cooking periods, but Jikokoa ownership cuts down the majority of this reduction ([Table A5](#)). To factor in that adoption reduces the time spent cooking, we conduct a complementary analysis of pollution during ‘cooking hours’, which we define as 6-8am and 7-9pm following [Figure 5](#). In line with the results above, improved cookstove ownership causes an environmentally and statistically large reduction in PM2.5 air pollution during these hours.

However, importantly, columns (2) and (4) indicate that there are no detectable effects on any of the other hours of the day. As a result, when looking at aggregate pollution exposure over the entire course of the day, Column (6) indicates that the reduction in air pollution during cooking hours has negligible effects on aggregate pollution exposure, given the high baseline levels of ambient air pollution. In this context, the reduction in cooking-related pollution cause only a small reduction and statistically undetectable in total pollution exposure. The limited contribution of indoor air pollution to aggregate air pollution when compared with outdoor air pollution departs from previous research on this topic (Fisher et al., [2021](#)) and has important policy implications (Gill-Wiehl and Kammen, [2022](#)).

Again, the lack of impact on aggregate exposure can be easily reconciled when considering the high ambient pollution levels, which remain unchanged. Median non-cooking exposure to PM2.5 is around $25\mu\text{g}/\text{m}^3$ (this is in line with Pope et al. [\(2018\)](#), who find urban roadside levels of $36.6\mu\text{g}/\text{m}^3$ and background of $24.8\mu\text{g}/\text{m}^3$). Cooking increases PM2.5 by around $9\text{--}19\mu\text{g}/\text{m}^3$ (decomposition suggests cooking increases PM 2.5 by around $9\mu\text{g}/\text{m}^3$ while comparing hours suggests $19\mu\text{g}/\text{m}^3$). Even if cooking increases PM2.5 by $25\mu\text{g}/\text{m}^3$, average exposure would still increase from $35\mu\text{g}/\text{m}^3$ to only $37.25\mu\text{g}/\text{m}^3$ - a less than 7% increase in average pollution exposure.

We can conduct a back-of-the-envelope exercise to get a sense for what pollution exposure reduction might be in rural areas, where background air pollution is $9\mu\text{g}/\text{m}^3$ (Pope et al., [2018](#)). Even conservatively supposing that participants cook for twice as long in rural areas as in urban areas, this would still only generate a 22% reduction in aggregate exposure.

Columns (5)–(8) of [Table 3](#) indicate no impacts on CO. This is in line with recent independent laboratory tests scoring the Jikokoa Tier 3 for PM2.5 but Tier 1 for CO (CREEC [2022](#)). A stove’s CO output generally depends on its rate of oxygenation: higher oxygen inflow increases the production of CO₂ and reduces the production of CO while cooking. Per the company’s engineers, the lack of reduction in CO output results from a desire to increase the durability of the stove by limiting peak cooking temperatures to 700°C. While this improves durability, it limits oxygenation.

4.3 Impacts of stove ownership on health

[Table 4](#) presents the primary estimates from the instrumental variables approach described in [Equation 1](#), of the impact of stove adoption on health outcomes, controlling flexibly for age and linearly for other socioeconomic outcomes measured at baseline. Column (2) uses 2022 Jikokoa ownership as the endogenous variable while Column (3) uses 2019 Jikokoa adoption as the endogenous variable. The first five outcomes are quantitative measurements. The next seven outcomes are self-reported health outcomes, while the final three outcomes measure health expenditures. Following our pre-analysis plan ([Berkouwer and Dean, 2022b](#)) we separate self-reported health symptoms into those related to the respiratory system and those not.

The results indicate a 0.22 standard deviation reduction in self-reported symptoms related to respiratory concerns, such as sore throat, headache, and cough ([Table A7](#) present more detailed results on symptoms). While some of these results may be driven by experimenter demand, [Section 4.4](#) presents suggestive evidence for why there is likely to be at least some signal in these results.

However, we identify no long-term health improvements in quantitatively measured outcomes such as blood oxygen and blood pressure, self-reported non-respiratory symptoms, and self-reports about any diagnoses made by a medical professional during a hospital visit ([Table A9](#) presents more detailed results on medical diagnoses). Finally, we find no effect on the number of hospital visits or on hospital-related expenditures.

Taken together, the results on pollution and health may indicate important heterogeneity in the impacts of pollution exposure on health. Specifically, the reduction in peak exposure may reduce short-term self-reported symptoms such as having a sore throat, but the lack of reduction in aggregate average pollution exposure may explain the lack of impacts on chronic or quantitative health outcomes, despite 3.5 years of sustained use of reduced peaks in air pollution. [Section 5](#) explores this possible relationship in more detail.

Background ambient pollution is another potentially important source of heterogeneity, as some previous research has found air pollution improvements to be non-linear—either concave or convex—in average pollution. We test for heterogeneity in the primary treatment effect on health by whether the respondent has above or below median ambient air pollution. To avoid bias due to adoption endogeneity and noise in the time use data, we define a respondent’s ambient pollution as average pollution among the five respondents residing nearest that respondent. We then test whether the health impacts differ by whether respondents whose ambient exposure is above vs the median. We find no difference of heterogeneity along this dimension, at least over the range of pollution levels we observe ([Table A10](#)). Of course, we cannot rule out that the relationship between health and pollution is concave at other parts of the distribution. We do not find evidence of heterogeneity in treatment impacts along the lines of age, WTP, or baseline beliefs about future health impacts ([Table A12](#)).

While the short-term impact of air pollution has been noted before, our results differ from previous research (see for example [Chang et al., 2015](#); [Kubesch et al., 2015](#); [Soppa et al., 2014](#))

Table 4: Primary health outcomes

| | Control Mean (1) | Treatment Effect (2022 Ownership) (2) | Treatment Effect (2019 ownership) (3) | N |
|---|------------------------|---|---|-----|
| Average systolic blood pressure | 122.16 [18.97] | 0.34 (3.22) | 0.12 (2.36) | 696 |
| Average diastolic blood pressure | 81.32 [11.73] | 0.58 (2.12) | 0.38 (1.56) | 696 |
| Hypertension: Stage 1 or higher ($>130/80$) | 0.51 [0.50] | 0.03 (0.09) | 0.02 (0.06) | 696 |
| Hypertension: Stage 2 or higher ($>140/90$) | 0.27 [0.44] | -0.03 (0.08) | -0.02 (0.06) | 696 |
| Blood oxygen | 96.61 [2.53] | 0.35 (0.36) | 0.23 (0.26) | 696 |
| Number of non-respiratory health symptoms | 1.09 [1.54] | -0.19 (0.26) | -0.15 (0.19) | 702 |
| Non-respiratory health symptom index | -0.00 [1.00] | -0.00 (0.19) | -0.00 (0.14) | 702 |
| Number of respiratory health symptoms | 1.70 [1.76] | -0.45* (0.23) | -0.33* (0.17) | 702 |
| Respiratory health symptom index | -0.00 [1.00] | -0.22* (0.13) | -0.16* (0.10) | 702 |
| Health diagnoses index | 0.00 [1.00] | 0.14 (0.16) | 0.10 (0.12) | 702 |
| Number of health diagnoses | 0.30 [0.58] | 0.13 (0.09) | 0.10 (0.07) | 702 |
| Cognitive index | 0.00 [1.00] | -0.00 (0.16) | -0.02 (0.13) | 568 |
| Non-hospital health expenditures (USD) | 4.34 [7.64] | 0.78 (1.07) | 0.55 (0.79) | 702 |
| Hospital visits in past 30 days | 0.33 [0.57] | -0.01 (0.09) | -0.01 (0.07) | 702 |
| Hospital visit expenditures (USD) | 3.39 [11.17] | 1.23 (1.47) | 0.94 (1.07) | 702 |

Each row is a regression wherein endline modern stove use is instrumented for with baseline BDM price. Regressions control for baseline demographic and socioeconomic characteristics. [Table A7](#), [Table A9](#), and [Table A11](#) present detailed results on the components of the symptoms, diagnoses, and cognitive indices, respectively.

documenting an association with blood pressure within 1–2 hours of high pollution exposure.

We do find a meaningful increase in the number of symptoms reported regarding young children. This is driven by increases in breathlessness and cough ([Table A8](#)). Given the smaller sample size, and the number of statistical tests presented in these results, we attribute this to statistical noise and refrain from commenting on what might be causing this puzzling result.

We see no impacts of adoption on any of the cognition outcomes ([Table A11](#)).¹⁸

¹⁸Due to a technical issue with the tablets the sample size for some of the cognition outcomes is smaller than in other outcome tables. Since this was a technical issue, and since the order of follow-up surveys was randomized, it is

4.4 Robustness tests

A critical concern when using self-reported data is whether self-reports are driven by experimenter demand. Participants who received a (sometimes very heavily) subsidized cookstove might be more inclined to report better health than those who did not. While we cannot rule out some amount of experimenter demand, several factors weigh against this fully explaining the effects. First, we test whether those with higher subsidies are more likely to report positive health. If respondents with a lower price (higher subsidy) were more likely to self-report better health, price would correlate directly with self-reported symptoms rather than purely through the adoption channel ('owns jikokoa'). We do not find evidence of this ([Table A15](#)). Second, self-reported health improvements arise primarily through respiratory rather than non-respiratory symptoms: participants would thus have to be sophisticated about which types of health symptoms they report improvements in. Third, the relationship between health and pollution is similar in magnitude when constraining the sample to either just adopters or to just non-adopters, though the estimates are no longer significant due to the smaller sample size ([Table A18](#) and [Table A19](#)).

702 of the 942 respondents (75%) were surveyed successfully during the three-year follow-up survey. Attrition is not correlated with their randomly assigned BDM price, credit treatment assignment, initial Jikokoa stove adoption, or baseline health outcomes ([Table A13](#)). Attrition is slightly higher among respondents with fewer children, fewer household members, and younger respondents (such respondents may more easily move around, making them harder to track).

5 The relationship between pollution and health

There is uncertainty in the literature about which moments of the pollution exposure matter for health. Unfortunately using an instrumental variables approach to estimate the impacts of these different moments causally lacks precision (the Cragg-Donald Wald F-statistic on a weak identification test is 1.4) and also potentially violates the exclusion restriction as there are multiple channels through which stove adoption could affect health outcomes (including the financial savings from reduced charcoal expenditures).

Instead, we provide some evidence by using standard OLS regressions to estimate three key moments: average pollution exposure (in $100\mu\text{g}/\text{m}^3$), peak pollution exposure (defined as the highest hourly average recorded, in $100\mu\text{g}/\text{m}^3$), and the duration of high pollution exposure (defined as the number of hours pollution was above in $100\mu\text{g}/\text{m}^3$). [Table 5](#) presents the results. Columns (4) and (6) control for average pollution to look at the effect of peakiness as distinct from higher average pollution.

Mean or median PM2.5 air pollution are not correlated with self-reported health symptoms, whereas maximum hourly pollution is. This points to important heterogeneity in the impacts of maximum air pollution exposure rather than mean daily levels that were investigated in much of the literature studying ambient air pollution, such as Chay and Greenstone ([2003](#)), Clay et al. ([2022](#)),

unlikely that this biased the results in any meaningful way.

Table 5: Correlation between health and mean, median, maximum, and duration of PM2.5 exposure

| | Mean SD | Mean Pollution (SD) | Median Pollution (SD) | Max Hourly Pollution (SD) | Hours Above $100\mu\text{g}/\text{m}^3$ | N |
|-----------------------------------|-----------------|---------------------------|-----------------------------|---------------------------------|---|-----|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hypertension ($>130/80$) | 0.51 [0.50] | 0.01 (0.02) | -0.01 (0.02) | 0.01 (0.02) | -0.00 (0.01) | 645 |
| Blood oxygen | 96.72 [2.43] | 0.11 (0.10) | 0.11 (0.10) | -0.01 (0.10) | 0.02 (0.05) | 645 |
| Number of health symptoms | 2.52 [2.66] | -0.02 (0.10) | -0.02 (0.10) | 0.20** (0.10) | 0.02 (0.06) | 651 |
| Health symptoms index (z-score) | -0.09 [0.92] | -0.01 (0.04) | -0.02 (0.04) | 0.06* (0.04) | 0.00 (0.02) | 651 |
| Number of health diagnoses | 0.29 [0.56] | -0.03 (0.02) | -0.01 (0.02) | -0.00 (0.02) | -0.02 (0.01) | 651 |
| Health diagnoses index | -0.04 [0.89] | -0.05 (0.04) | -0.05 (0.04) | -0.01 (0.04) | -0.03 (0.02) | 651 |
| Hospital visits in past 30 days | 0.30 [0.55] | -0.00 (0.02) | -0.00 (0.02) | 0.01 (0.02) | 0.00 (0.01) | 651 |
| Hospital visit expenditures (USD) | 2.82 [10.14] | 0.29 (0.41) | 0.08 (0.42) | 0.36 (0.41) | 0.17 (0.23) | 651 |

Each row and column cell in columns (2)–(5) is a separate OLS regression. All regressions control for baseline socioeconomic and demographic characteristics. Hypertension refers to stage 1. [Table A16](#) provides the same for CO. [Table A17](#) provides a version with additional detail. [Table A7](#) and [Table A9](#) present detailed results on symptoms and diagnoses. [Table A18](#) and [Table A19](#) present the same for

[Currie and Walker \(2011\)](#), [Deryugina et al. \(2019\)](#), [Ebenstein et al. \(2017\)](#), [Greenstone and Hanna \(2014\)](#), [Isen et al. \(2017\)](#), and [Schlenker and Walker \(2015\)](#).

6 Conclusion

Academic literatures on indoor and outdoor air pollution have primarily focused on these topics in isolation, despite the fact that many of the world’s urban poor face both on a daily basis. Importantly, the presence of high ambient air pollution may dampen the health improvements derived from the private adoption of improved air quality technologies. Disentangling the health impacts of household and ambient air pollution has important implications for whether urban environmental health can be improved through private actions or requires government intervention addressing negative environmental externalities.

We investigate the interaction of these two sources of individual pollution exposure by leveraging an urban randomized experiment of improved biomass cookstoves among 1,000 households in Nairobi, Kenya. The analyses generate several key findings. First, adoption of a more energy efficient biomass cookstove causes a large reduction in air pollution generated during cooking hours,

even more than three years after initial adoption. Households experience a 0.22 standard deviation improvement in self-reported respiratory symptoms, and save on average USD 1.50 (39%) in weekly energy expenditures.

However, since we observe no reduction during the remaining 22 hours of the day, and given the high levels of ambient pollution in this urban context, we see only a very small and statistically insignificant effect on aggregate air pollution exposure. These washed out pollution impacts can explain the comprehensive lack of impacts on a host of quantitative health measurements (including blood pressure and blood oxygen) and self-reported diagnoses of chronic diseases such as pneumonia.

Adoption of clean cooking technologies may have a larger impact on health in rural areas, where ambient pollution levels tend to be lower. In Kenya, background is approximately $9\mu g/m^3$ Pope et al. (2018). Even assuming participants cook for twice as many minutes each day in rural areas as in urban areas, this would lead to a 22% reduction in aggregate exposure. Corroborating this back-of-the-envelope calculation, and understanding the impacts on health, is left as future work.

The results above suggest that the urban poor have only limited ability to improve their environmental health through the private adoption of improved technologies. Instead, improving chronic and long-term health will depend on the reduction of ambient air pollution, which will require government intervention addressing the negative pollution externality caused by economic activity.

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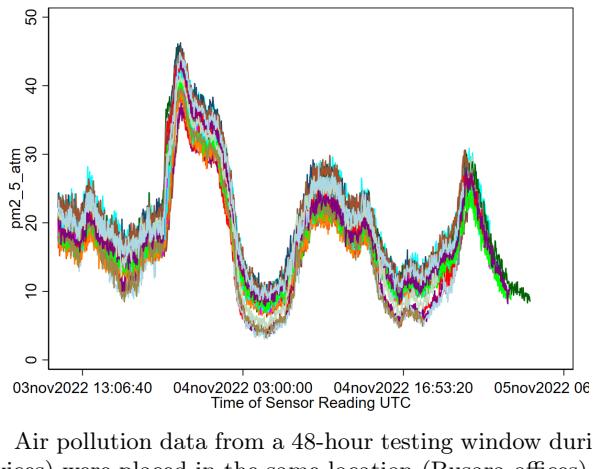
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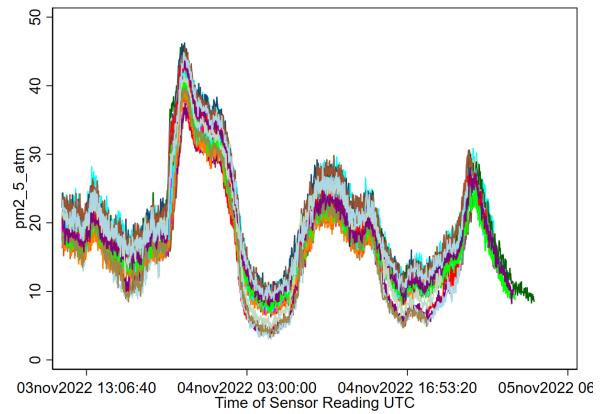
A Appendix Figures

Figure A1: Co-located air pollution readings for devices

A) PM2.5 (PA-II devices)



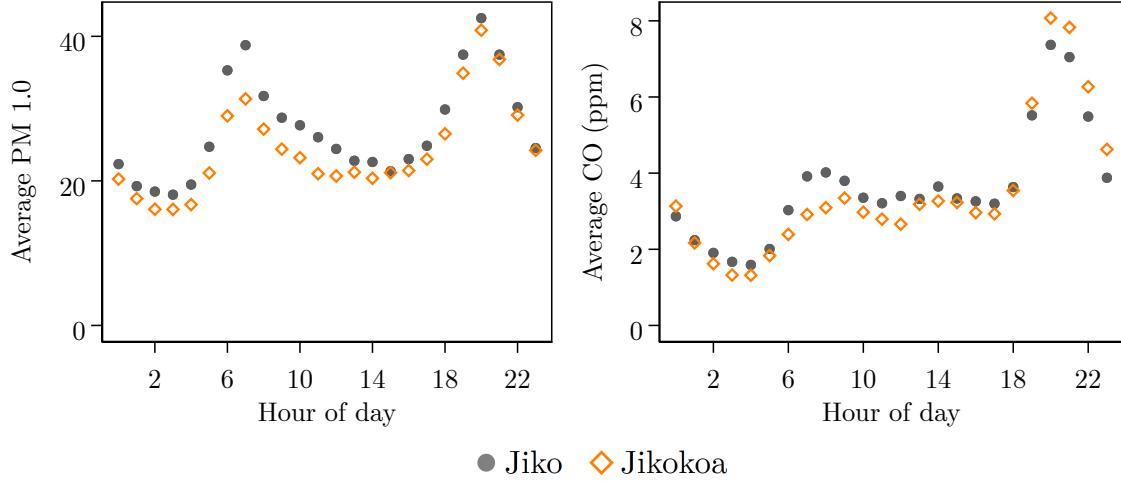
B) CO (LASCAR devices)



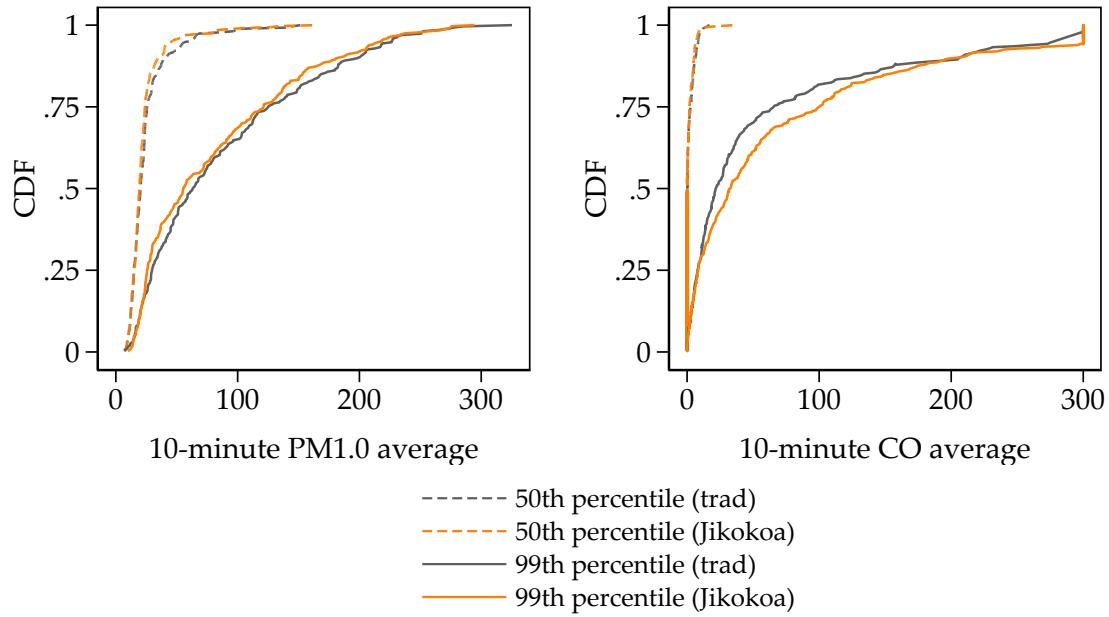
Air pollution data from a 48-hour testing window during which all 68 devices (34 PA-II devices and 34 LASCAR devices) were placed in the same location (Busara offices).

Figure A2: Particulate matter (PM1.0, in $\mu\text{g}/\text{m}^3$) and Carbon Monoxide pollution by Jikokoa ownership

A) Average hourly exposure over the hours of the day

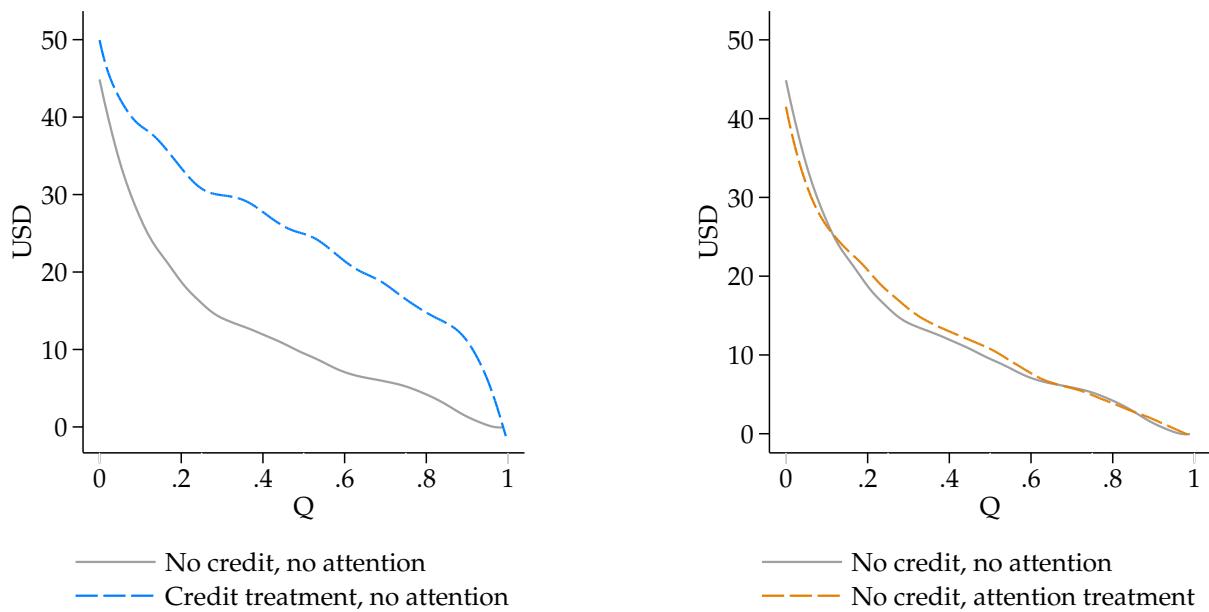


B) Distribution of 10th and 50th percentile of 10-minute concentrations, across individuals



Panel A presents average PM1.0 and CO exposure by hour of day and endline Jikokoa ownership, as collected by respondents wearing backpacks for on average 48 hours. Panel B presents the distribution of mean and 99th percentile 10-minute average exposure across respondents. [Figure 4](#) presents the same for PM2.5.

Figure A3: Impacts of experimental treatments on WTP
 Panel (A) Panel (B)

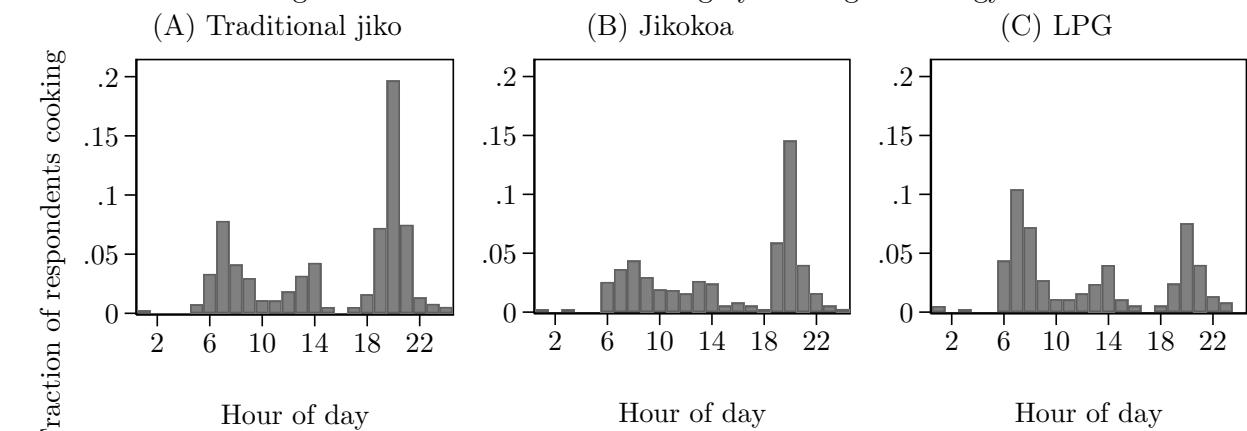


Note: This figure has been reproduced in its entirety from Berkouwer and Dean (2022a). Graphs show the cumulative distribution of WTP for the control and treatment groups for both experimental treatments. Panel A presents results by credit treatment status among people in the attention control group only. Panel B presents results by attention treatment status among people in the credit control group only. Access to credit increases WTP by USD 13 (104 percent relative to control). Attention to benefits does not affect WTP.



Panel A shows a Purple Air Inc. device, which records PM1.0 and PM2.5 readings every 2 minutes. Panel B shows a Lascar Electronics device, which records one CO reading every minute. Panel C displays how the devices are affixed to a lightweight foam material to stay in place. Behind the purple air device is a battery. Panel D displays the final backpack as deployed with respondents.

Figure A5: Time use data: cooking by cooking technology



Fraction of respondents who report using a particular cooking technology across the various hours of the day.

B Appendix Tables

Table A1: Pollution during self-reported time use activities

| Activity | Hours | Pm 2.5 |
|-------------|----------------|------------------|
| Cooking | 3.10 (1.61) | 38.98 (25.47) |
| Sleeping | 9.59 (4.55) | 29.71 (16.53) |
| Eating | 3.55 (1.35) | 39.47 (26.42) |
| Bus | 0.32 (0.80) | 31.95 (19.95) |
| Bicycle | 0.03 (0.25) | 36.18 (40.21) |
| Walking | 1.66 (1.71) | 32.45 (21.97) |
| Work | 2.26 (2.17) | 34.35 (23.31) |
| Schoolwork | 0.09 (0.35) | 37.13 (29.30) |
| Other(away) | 0.60 (1.08) | 36.24 (28.57) |
| Other(home) | 3.57 (3.07) | 35.33 (19.09) |

Average hourly air pollution matched with hourly self-reported time use data, collected during the 2022–2023 endline survey.

Table A2: First stage: impact of random treatments on take-up

| | (1) | (2) | (3) | (4) | (5) |
|-----------------------------------|-------------------|--------------------|--------------------|--------------------|--------------------|
| Credit treatment | 0.29*** (0.04) | | 0.30*** (0.04) | 0.21*** (0.08) | 0.21** (0.08) |
| Price (10 USD) | | -0.20*** (0.02) | -0.20*** (0.02) | -0.23*** (0.03) | -0.23*** (0.03) |
| Credit treatment X Price (10 USD) | | | | 0.00 (0.00) | 0.00 (0.00) |
| Socioeconomic controls | No | No | No | No | Yes |
| Observations | 702 | 702 | 702 | 702 | 702 |

Impact of randomly assigned price, credit treatment status, and their interaction on Jikokoa ownership, estimated using OLS.

Table A3: Causal impact of cookstove adoption on pollution exposure

Panel A) Between 6–8am and 6–9pm (when most respondents report cooking)

| | PM2.5 | | | | CO | | | |
|--------------|---------------|-----------------|-------------------|------------------|---------------|--------------|-----------------|----------------|
| | (1) Median | (2) Mean | (3) Max Hour | (4) 99th | (5) Median | (6) Mean | (7) Max Hour | (8) 99th |
| Own Jikokoa | -5.9 (4.1) | -9.8** (4.9) | -27.8** (12.1) | -25.7* (15.2) | 2.0 (2.4) | 4.8 (3.3) | 16.3 (11.2) | 17.9 (16.1) |
| Control Mean | 37.4 | 50.0 | 101.8 | 152.4 | 3.4 | 9.3 | 32.7 | 53.9 |

Panel B) When self-reporting not cooking

| | PM2.5 | | | | CO | | | |
|--------------|---------------|---------------|-----------------|-----------------|---------------|--------------|-----------------|----------------|
| | (1) Median | (2) Mean | (3) Max Hour | (4) 99th | (5) Median | (6) Mean | (7) Max Hour | (8) 99th |
| Own Jikokoa | 0.4 (1.8) | -1.8 (2.9) | -18.3 (12.6) | -18.5 (14.9) | -0.6 (0.4) | 1.6 (1.6) | 12.2 (12.6) | 14.9 (14.7) |
| Control Mean | 24.5 | 34.6 | 118.2 | 154.4 | 1.8 | 5.9 | 43.9 | 55.2 |

Instrumental variables regression where the randomly assigned price, credit treatment status, and their interaction are used as instruments for endline Jikokoa ownership. All PM2.5 regressions have 590 observations and a Weak IV F-statistic of 48. All CO regressions have 607 observations and a Weak IV F-statistic of 49. Columns (1) and (5) use median exposure, (2) and (6) use mean exposure, (3) and (7) use maximum 1-hour average exposure, and (4) and (8) use 99th percentile of 10-min average exposure. Regressions include baseline demographic and socioeconomic controls and fixed effects for the specific LASCAR or PA-II device used for that respondent. Table 3 presents the same for all hours and for when self-reporting cooking. Table A4 presents all four outcomes in logs.

Table A4: Causal impact of cookstove adoption on pollution exposure (in logs)

Panel A) All

| | PM2.5 | | | | CO | | |
|---------------------|----------------|-----------------|------------------|-----------------|----------------|-----------------|------------------|
| | (1) Median | (2) Mean | (3) Max Hour | (4) 99th | (5) Mean | (6) Max Hour | (7) 99th |
| Own Jikokoa | 0.01 (0.06) | -0.07 (0.08) | -0.22* (0.12) | -0.20 (0.13) | 0.55 (0.33) | 0.53* (0.31) | 0.57** (0.28) |
| Control Mean | 3.1 | 3.5 | 4.7 | 4.9 | 0.6 | 2.8 | 3.1 |
| Weak IV F-Statistic | 49 | 49 | 49 | 49 | 53 | 53 | 53 |
| Observations | 597 | 597 | 597 | 597 | 653 | 652 | 645 |

Panel B) When self-reporting cooking

| | PM2.5 | | | | CO | | |
|---------------------|-----------------|------------------|-------------------|------------------|----------------|-----------------|----------------|
| | (1) Median | (2) Mean | (3) Max Hour | (4) 99th | (5) Mean | (6) Max Hour | (7) 99th |
| Own Jikokoa | -0.06 (0.10) | -0.19* (0.11) | -0.31** (0.14) | -0.31* (0.16) | 0.25 (0.41) | 0.24 (0.40) | 0.23 (0.36) |
| Control Mean | 3.3 | 3.6 | 4.0 | 4.4 | 1.0 | 2.0 | 2.6 |
| Weak IV F-Statistic | 49 | 49 | 49 | 49 | 46 | 46 | 46 |
| Observations | 597 | 597 | 596 | 597 | 547 | 545 | 547 |

Panel C) Between 6–8am and 6–9pm (when most respondents report cooking)

| | PM2.5 | | | | CO | | |
|---------------------|-----------------|------------------|-------------------|------------------|----------------|-----------------|----------------|
| | (1) Median | (2) Mean | (3) Max Hour | (4) 99th | (5) Mean | (6) Max Hour | (7) 99th |
| Own Jikokoa | -0.09 (0.09) | -0.17* (0.10) | -0.29** (0.13) | -0.25* (0.14) | 0.38 (0.37) | 0.46 (0.35) | 0.34 (0.32) |
| Control Mean | 3.5 | 3.8 | 4.4 | 4.8 | 1.0 | 2.3 | 2.9 |
| Weak IV F-Statistic | 49 | 49 | 49 | 49 | 51 | 51 | 51 |
| Observations | 597 | 597 | 594 | 597 | 628 | 628 | 628 |

Panel D) When self-reporting not cooking

| | PM2.5 | | | | CO | | |
|---------------------|----------------|-----------------|-----------------|-----------------|----------------|-----------------|-----------------|
| | (1) Median | (2) Mean | (3) Max Hour | (4) 99th | (5) Mean | (6) Max Hour | (7) 99th |
| Own Jikokoa | 0.00 (0.06) | -0.06 (0.08) | -0.20 (0.13) | -0.18 (0.13) | 0.44 (0.34) | 0.48 (0.32) | 0.51* (0.28) |
| Control Mean | 3.1 | 3.4 | 4.6 | 4.9 | 0.5 | 2.6 | 3.0 |
| Weak IV F-Statistic | 49 | 49 | 49 | 49 | 53 | 53 | 52 |
| Observations | 597 | 597 | 597 | 597 | 649 | 650 | 637 |

Instrumental variables regression where the randomly assigned price, credit treatment status, and their interaction are used as instruments for endline Jikokoa ownership. All PM2.5 regressions have 590 observations and a Weak IV F-statistic of 48. Observations vary across CO regressions because of the high occurrence of 0s. Columns (1) and (5) use median exposure, (2) and (6) use mean exposure, (3) and (7) use maximum 1-hour average exposure, and (4) and (8) use 99th percentile of 10-min average exposure. Regressions include baseline demographic and socioeconomic controls and fixed effects for the specific LASCAR or PA-II device used for that respondent. Table 3 presents the same for all hours and for when self-reporting cooking A-7

Table A5: Causal impact of cookstove adoption on pollution exposure using hourly data

| | Cooking | PM 2.5 | | PM 1.0 | | CO | |
|-------------------------|--------------------|-------------------|-------------------|-------------------|-------------------|-------------------|------------------|
| | (1) IV | (2) OLS | (3) IV | (4) OLS | (5) IV | (6) OLS | (7) IV |
| Own Jikokoa | -0.03*** (0.01) | -1.11 (1.36) | -0.62 (2.61) | -0.71 (0.97) | -0.31 (1.89) | 1.53** (0.71) | 3.24** (1.33) |
| Cooking and Own Jikokoa | | -6.09** (2.38) | -6.95 (5.47) | -4.03** (1.78) | -5.09 (4.24) | 1.92 (1.63) | -1.53 (3.66) |
| Cooking | | 7.61*** (1.98) | 8.08*** (2.92) | 5.41*** (1.49) | 5.99*** (2.26) | 3.57*** (1.09) | 5.48** (2.17) |
| DoW*HoD*Geocluster FE | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Control Mean | 0.10 | 34.28 | 34.28 | 25.45 | 25.45 | 5.80 | 5.80 |
| Weak IV F-Statistic | 34 | | 32 | | 32 | | 32 |
| Households | 650 | 650 | 650 | 650 | 650 | 656 | 656 |
| Observations | 28743 | 23340 | 23340 | 23340 | 23340 | 28960 | 28960 |

Standard errors clustered by respondent. All regressions include week FE; device FE; the interaction of and hour-of-day by day-of-week by neighborhood FE; as well as baseline demographic and socioeconomic controls.

Table A6: More detailed socio-economic outcomes

| | Control Mean | Treatment Effect | N |
|---|-------------------|---------------------|-----|
| Charcoal expenditures past 7 days (USD) | 3.84 [3.16] | -1.37*** (0.48) | 702 |
| Charcoal expenditures past 7 days (log) | 5.98 [0.82] | -0.31** (0.12) | 667 |
| Earnings past 2 weeks (USD) | 32.53 [35.41] | 7.24 (7.80) | 563 |
| Has formal bank account (=1) | 0.13 [0.34] | 0.10 (0.07) | 702 |
| Total savings (USD) | 53.64 [86.62] | -3.83 (19.53) | 701 |
| ... in mobile banking (USD) | 5.85 [12.29] | -1.39 (2.41) | 702 |
| ... contributions to SACCO (USD) | 7.93 [14.30] | 1.78 (2.83) | 701 |
| ... in SACCO payout (USD) | 40.25 [64.75] | -9.97 (13.59) | 701 |
| ... in formal banking (USD) | 7.63 [34.99] | 7.46 (8.66) | 702 |
| Minutes cooking per day | 136.72 [57.76] | -2.56 (10.19) | 702 |
| ... minutes in the morning | 30.97 [18.73] | -1.28 (2.94) | 702 |
| ... minutes in the afternoon | 40.53 [25.05] | -0.47 (4.74) | 702 |
| ... minutes in the evening | 65.22 [31.56] | -0.82 (5.78) | 702 |
| People in network who adopted Jikokoa | 0.78 [2.04] | 0.90** (0.41) | 702 |
| ... neighbors | 0.28 [0.82] | 0.46*** (0.17) | 702 |
| ... family members | 0.20 [0.69] | 0.16 (0.13) | 702 |
| ... friends | 0.20 [0.69] | 0.17 (0.13) | 702 |
| ... other people | 0.10 [0.45] | 0.10 (0.10) | 702 |

Table A7: Health symptoms - Adult

| | Control Mean | Treatment Effect | N |
|---|-----------------|---------------------|-----|
| Health symptoms index (z-score) | 0.00 [1.00] | -0.13 (0.16) | 702 |
| Number of health symptoms | 2.78 [2.93] | -0.66 (0.42) | 702 |
| Fever | 0.20 [0.40] | 0.02 (0.07) | 702 |
| Malaria | 0.15 [0.36] | -0.12* (0.07) | 702 |
| Persistent cough | 0.24 [0.43] | -0.08 (0.07) | 702 |
| Typhoid | 0.02 [0.14] | 0.01 (0.02) | 702 |
| Always feeling tired | 0.30 [0.46] | -0.04 (0.07) | 702 |
| Tuberculosis | 0.01 [0.08] | -0.00 (0.02) | 702 |
| Stomach pain | 0.16 [0.37] | -0.11* (0.06) | 702 |
| Pain when urinating | 0.01 [0.10] | -0.01 (0.03) | 702 |
| Worms | 0.01 [0.11] | 0.05** (0.02) | 702 |
| Cholera | 0.00 [0.00] | 0.01 (0.01) | 702 |
| Rapid weight loss | 0.06 [0.24] | -0.08* (0.04) | 702 |
| Breathlessness at night | 0.08 [0.27] | -0.01 (0.04) | 702 |
| Frequent diarrhea | 0.02 [0.15] | -0.02 (0.03) | 702 |
| Frequent and excessive urination | 0.03 [0.16] | 0.01 (0.02) | 702 |
| Skin Rash or irritation | 0.02 [0.12] | 0.04 (0.03) | 702 |
| Constant thirst / increased drinking of fluids | 0.14 [0.35] | 0.01 (0.05) | 702 |
| Difficulty swallowing | 0.03 [0.17] | -0.01 (0.02) | 702 |
| Difficulty breathing / Chest tightness | 0.07 [0.26] | -0.01 (0.04) | 702 |
| Runny nose | 0.23 [0.42] | -0.05 (0.07) | 702 |
| Sore throat | 0.16 [0.37] | -0.11* (0.06) | 702 |
| Muscle pain (myalgia) | 0.12 [0.32] | -0.00 (0.05) | 702 |
| Headache | 0.52 [0.50] | -0.12 (0.08) | 702 |
| Loss of sense of smell / not being able to taste food | 0.05 [0.21] | -0.01 (0.03) | 702 |
| Diarrhea / Nausea / Vomiting | 0.05 [0.21] | -0.04 (0.03) | 702 |
| Wheezing | 0.03 [0.17] | 0.01 (0.03) | 702 |
| Persistent mucus problems | 0.04 [0.19] | -0.01 (0.02) | 702 |
| Swelling in ankles, feet or legs | 0.04 [0.20] | 0.00 (0.03) | 702 |
| Other accidents | 0.02 [0.14] | 0.07*** (0.03) | 702 |

Each row is a regression wherein endline modern stove use is instrumented for with baseline BDM price.
 Regressions control for respondent age and sex.

Table A8: Symptoms - Child

| | Control Mean | Treatment Effect | N |
|--|-----------------|---------------------|-----|
| Child health symptom index | -0.00 [1.00] | 0.14 (0.26) | 352 |
| Fever | 0.17 [0.38] | -0.02 (0.08) | 352 |
| Vomiting | 0.10 [0.30] | -0.01 (0.06) | 352 |
| Cough | 0.41 [0.49] | 0.01 (0.11) | 352 |
| Diarrhea | 0.10 [0.30] | -0.02 (0.07) | 352 |
| Breathlessness | 0.04 [0.19] | 0.08 (0.05) | 352 |
| Persistent headache | 0.08 [0.27] | 0.03 (0.05) | 352 |
| Any other infection | 0.01 [0.11] | 0.02 (0.03) | 352 |
| Short, rapid breaths, or difficulty breathing (past 2 weeks) | 0.04 [0.19] | 0.08 (0.05) | 352 |
| Very bad cough | 0.25 [0.43] | 0.10 (0.08) | 352 |

Each row is a regression wherein endline modern stove use is instrumented for with baseline BDM price. Symptoms for children under five as reported by the primary cookstove user (usually a caretaker of the child).

Table A9: Diagnoses by a doctor

| | Control Mean | Treatment Effect | N |
|----------------------------------|-----------------|---------------------|-----|
| Number of health diagnoses | 0.30 [0.58] | 0.11 (0.09) | 702 |
| Asthma | 0.01 [0.08] | -0.01 (0.01) | 702 |
| Pneumonia | 0.13 [0.34] | -0.01 (0.05) | 702 |
| Chronic Pulmonary Disease | 0.00 [0.06] | 0.01 (0.01) | 702 |
| Tuberculosis | 0.01 [0.08] | 0.02 (0.01) | 702 |
| COVID | 0.01 [0.08] | -0.01 (0.00) | 702 |
| Other lung disease | 0.01 [0.08] | -0.01 (0.01) | 702 |
| Stroke or cardiovascular disease | 0.01 [0.08] | -0.00 (0.01) | 702 |
| Hypertension | 0.05 [0.22] | 0.10*** (0.04) | 702 |
| Diabetes | 0.02 [0.14] | 0.00 (0.02) | 702 |
| Other | 0.04 [0.19] | 0.01 (0.03) | 702 |

Each row is a regression wherein endline modern stove use is instrumented for with baseline BDM price.
 Regressions control for respondent age and sex.

Table A10: Primary health outcomes by ambient concentrations

| | Treatment (1) | Treatment X Ambient (2) | N |
|---|------------------|-------------------------------|-----|
| Average systolic blood pressure | -1.12 (4.84) | 3.62 (6.13) | 649 |
| Average diastolic blood pressure | 0.88 (2.93) | 0.25 (4.06) | 649 |
| Hypertension: Stage 1 or higher (>130/80) | 0.03 (0.12) | -0.02 (0.17) | 649 |
| Hypertension: Stage 2 or higher (>140/90) | -0.04 (0.10) | 0.08 (0.14) | 649 |
| Blood oxygen | 0.05 (0.43) | 0.20 (0.67) | 649 |
| Number of non-respiratory health symptoms | 0.16 (0.30) | -0.80 (0.53) | 655 |
| Non-respiratory health symptom index | 0.15 (0.22) | -0.37 (0.39) | 655 |
| Number of respiratory health symptoms | -0.31 (0.30) | -0.05 (0.46) | 655 |
| Respiratory health symptom index | -0.13 (0.18) | -0.05 (0.26) | 655 |
| Health diagnoses index | -0.01 (0.25) | 0.24 (0.31) | 655 |
| Number of health diagnoses | 0.08 (0.13) | 0.10 (0.19) | 655 |
| Cognitive index | -0.33 (0.22) | 0.48 (0.33) | 528 |
| Non-hospital health expenditures (USD) | 1.47 (1.50) | -0.82 (2.33) | 655 |
| Hospital visits in past 30 days | 0.05 (0.12) | -0.12 (0.19) | 655 |
| Hospital visit expenditures (USD) | 0.94 (1.74) | 2.34 (3.10) | 655 |

 Observations

High ambient concentration is a dummy for above median average non-cooking PM2.5. Each row is a regression wherein endline modern stove use is instrumented for with baseline BDM price. Regressions control for baseline demographic and socioeconomic characteristics. [Table A7](#), [Table A9](#), and [Table A11](#) present detailed results on the components of the symptoms, diagnoses, and cognitive indices, respectively.

Table A11: Impacts on cognitive function

| | Control Mean | Treatment Effect | N |
|--|--------------------|---------------------|-----|
| Inhibitory Control (% Correct on HF) | 0.80 [0.19] | 0.02 (0.03) | 728 |
| Inhibitory Control (Reaction Time on HF) | 812.71 [577.10] | 115.62 (97.08) | 728 |
| Working Memory (Max Corsi Length) | 4.98 [1.91] | 0.27 (0.44) | 417 |
| Attention (d2 score) | 50.92 [56.09] | 12.38 (9.92) | 805 |

Each row is a regression wherein endline modern stove use is instrumented for with baseline BDM price. Regressions control for baseline demographic and socioeconomic characteristics. See [Section 3.4](#) and [Appendix C](#) for descriptions of the cognitive exercises conducted to measure cognitive function. Due to a technical issues with the tablets not displaying the behavioral games, the sample size for some of the cognition outcomes is smaller than in other outcome tables. Since this was a technical issue that occurred in the earlier stages of the surveying round, and since the order of follow-up surveys was randomized, it is unlikely that this biased the results in any meaningful way.

Table A12: Heterogeneity in primary health impacts by baseline socioeconomic variables

| | Treatment X Age (1) | Treatment X WTP (2) | Treatment X Health (3) | Treatment X Health beliefs (4) | N |
|---|---------------------------|---------------------------|------------------------------|---|-----|
| Average systolic blood pressure | -0.66 (3.32) | -1.28 (4.77) | -2.32 (3.08) | -1.06 (3.43) | 696 |
| Average diastolic blood pressure | -2.50 (2.11) | -2.20 (3.04) | -3.67* (1.98) | -1.28 (2.32) | 696 |
| Hypertension: Stage 1 or higher (>130/80) | -0.01 (0.08) | -0.01 (0.12) | -0.16* (0.09) | -0.05 (0.09) | 696 |
| Hypertension: Stage 2 or higher (>140/90) | 0.03 (0.08) | -0.18 (0.12) | -0.15* (0.08) | -0.08 (0.08) | 696 |
| Blood oxygen | 0.12 (0.35) | 0.85 (0.60) | -0.19 (0.36) | -0.02 (0.38) | 696 |
| Number of non-respiratory health symptoms | 0.05 (0.20) | 0.30 (0.35) | 0.18 (0.21) | 0.09 (0.30) | 702 |
| Non-respiratory health symptom index | -0.03 (0.14) | 0.09 (0.23) | 0.14 (0.14) | 0.08 (0.22) | 702 |
| Number of respiratory health symptoms | 0.30 (0.21) | -0.01 (0.34) | -0.19 (0.21) | -0.07 (0.24) | 702 |
| Respiratory health symptom index | 0.15 (0.12) | -0.09 (0.19) | -0.10 (0.12) | -0.02 (0.13) | 702 |
| Observations | | | | | |

Each row is a regression wherein endline modern stove ownership and its interaction with the heterogeneity variable are instrumented for with randomly assigned credit treatment status, price, their interaction, as well as their three interactions with the heterogeneity variables. All heterogeneity variables are baseline measures and standardized to have mean 0 and standard deviation 1. All regressions include baseline controls.

Table A13: Attrition

| | Baseline Mean | Attrited | N |
|--|------------------|------------------|-----|
| BDM Price (USD) | 17.6 [8.3] | 0.3 (0.6) | 955 |
| Credit Treatment | 0.7 [0.5] | -0.0 (0.0) | 955 |
| Attention Treatment | 0.7 [0.5] | 0.1* (0.0) | 955 |
| Jikokoa (=1) | 0.6 [0.5] | -0.0 (0.0) | 955 |
| Persistent cough in past week | 0.3 [0.5] | -0.0 (0.0) | 955 |
| Persistent breathlessness in past week | 0.3 [0.5] | -0.0 (0.0) | 955 |
| Hours work missed due to health in past week | 3.2 [14.8] | 1.1 (1.1) | 951 |
| Female | 1.0 [0.2] | -0.0 (0.0) | 955 |
| Respondent age | 37.5 [11.8] | -3.8*** (0.9) | 955 |
| Number of household residents | 4.8 [2.1] | -0.4** (0.2) | 955 |
| Number of child residents | 2.6 [1.7] | -0.3* (0.1) | 955 |
| Savings in bank, mobile, ROSCA (USD) | 75.7 [130.2] | 11.8 (9.5) | 955 |
| Household income (USD/week) | 47.3 [34.8] | 2.5 (2.6) | 949 |
| Total energy consumption (USD/week) | 8.6 [3.6] | -0.4 (0.3) | 955 |
| Charcoal consumption (USD/week) | 5.6 [2.6] | -0.4* (0.2) | 955 |
| Price of old jiko (USD) | 3.4 [1.3] | 0.2 (0.1) | 950 |
| Risky investment amount (0-4 USD) | 1.2 [1.0] | -0.0 (0.1) | 955 |
| Mean | | 0.26 | |

All variables from baseline (2019). Attrited = 1 if respondent has not completed a 2022–2023 endline survey.

Table A14: Attrition: reaching participants

| Reason | Frequency |
|-------------------------------------|-----------|
| Completed survey | 702 |
| Unable to contact | 164 |
| Unavailable | 13 |
| Withdrew from study | 31 |
| Relocated outside survey team reach | 29 |
| Deceased | 7 |
| Imprisoned | 2 |
| Other | 9 |

Participants who we were unable to contact were labeled only after repeated phone calls to their phone numbers and to the phone numbers of family members, physical visits to their home locations, and inquiries with nearby participants.

Table A15: Testing for experimenter demand: direct effect of price on self-reported health

| | Respiratory | | | Non-respiratory | | |
|----------------------------|--------------------|-----------------|-----------------|--------------------|-----------------|-----------------|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Owns Jikokoa | -0.45*** (0.12) | -0.34 (0.28) | -0.37 (0.28) | -0.37*** (0.11) | -0.40 (0.26) | -0.40 (0.26) |
| Price (USD) | -0.00 (0.01) | 0.00 (0.01) | 0.00 (0.01) | -0.01 (0.01) | -0.01 (0.01) | -0.01 (0.01) |
| Owns Jikokoa X Price (USD) | | -0.01 (0.01) | -0.01 (0.01) | | 0.00 (0.01) | 0.00 (0.01) |
| WTP (USD) | | | 0.00 (0.01) | | -0.00 (0.00) | |

If respondents with a lower price (higher subsidy) were more likely to self-report better health, price would correlate directly with self-reported symptoms rather than through the adoption channel ('Owns Jikokoa'). We do not find evidence of this here.

Table A16: Correlation between health and mean, median, maximum, and duration of CO exposure

| | Mean SD (1) | Mean Pollution (SD) (2) | Median Pollution (SD) (3) | Max Hourly Pollution (SD) (4) | Hours Above 10coppm (5) | N (6) |
|---|-------------------|----------------------------------|------------------------------------|--|----------------------------------|----------|
| Average systolic blood pressure | 123.49 [21.60] | 1.35 (0.87) | 1.52 (0.99) | 0.81 (0.88) | -0.07 (0.27) | 645 |
| Average diastolic blood pressure | 81.74 [12.71] | 1.20** (0.54) | 0.41 (0.61) | 0.72 (0.54) | 0.08 (0.16) | 645 |
| Blood oxygen | 96.72 [2.43] | 0.23** (0.10) | 0.18 (0.11) | 0.20** (0.10) | 0.06** (0.03) | 645 |
| Number of health symptoms | 2.52 [2.66] | 0.12 (0.11) | 0.11 (0.12) | 0.18* (0.11) | 0.07** (0.03) | 651 |
| Health symptoms index (z-score) | -0.09 [0.92] | 0.05 (0.04) | 0.03 (0.04) | 0.07* (0.04) | 0.02** (0.01) | 651 |
| Number of non-respiratory health symptoms | 0.96 [1.44] | 0.05 (0.06) | 0.03 (0.07) | 0.12* (0.06) | 0.03* (0.02) | 651 |
| Non-respiratory health symptom index | -0.07 [0.99] | 0.04 (0.04) | 0.01 (0.05) | 0.08** (0.04) | 0.02 (0.01) | 651 |
| Number of respiratory health symptoms | 1.55 [1.60] | 0.07 (0.06) | 0.08 (0.07) | 0.06 (0.06) | 0.04** (0.02) | 651 |
| Respiratory health symptom index | -0.09 [0.88] | 0.05 (0.04) | 0.04 (0.04) | 0.03 (0.04) | 0.02* (0.01) | 651 |
| Number of health diagnoses | 0.29 [0.56] | 0.05* (0.02) | 0.03 (0.03) | 0.04 (0.02) | 0.01 (0.01) | 651 |
| Health diagnoses index | -0.04 [0.89] | 0.05 (0.04) | 0.03 (0.04) | 0.04 (0.04) | 0.00 (0.01) | 651 |

Each row and column cell in columns (2)–(5) is a separate OLS regression. All regressions control for baseline socioeconomic and demographic characteristics. Table 5 provides the same for PM2.5.

Table A17: Correlation between health and average, maximum, and duration of PM2.5 exposure

| | Mean SD | Average Pollution (<i>)</i> (1) | Max Hourly Pollution (<i>)</i> (3) | Hours Above $100\mu\text{g}/\text{m}^3$ (5) | N (7) | | |
|---|-------------------|---|--|--|-----------------|-----------------|-----|
| Average systolic blood pressure | 123.49 [21.60] | -0.37 (0.84) | 0.78 (0.82) | 1.67 (1.07) | 0.05 (0.47) | 0.96 (0.95) | 645 |
| Average diastolic blood pressure | 81.74 [12.71] | 0.52 (0.52) | 0.69 (0.51) | 0.60 (0.66) | 0.21 (0.29) | -0.18 (0.59) | 645 |
| Hypertension ($>130/80$) | 0.51 [0.50] | 0.00 (0.02) | 0.01 (0.02) | 0.01 (0.03) | -0.00 (0.01) | -0.01 (0.02) | 645 |
| Hypertension: Stage 2 or higher ($>140/90$) | 0.27 [0.44] | 0.00 (0.02) | 0.00 (0.02) | 0.00 (0.02) | -0.00 (0.01) | -0.00 (0.02) | 645 |
| Blood oxygen | 96.72 [2.43] | 0.11 (0.10) | 0.02 (0.10) | -0.09 (0.12) | 0.04 (0.05) | -0.07 (0.11) | 645 |
| Number of health symptoms | 2.52 [2.66] | -0.01 (0.10) | 0.18* (0.10) | 0.32** (0.13) | 0.02 (0.06) | 0.12 (0.11) | 651 |
| Health symptoms index (z-score) | -0.09 [0.92] | -0.01 (0.04) | 0.06* (0.03) | 0.11** (0.05) | 0.01 (0.02) | 0.05 (0.04) | 651 |
| Number of non-respiratory health symptoms | 0.96 [1.44] | 0.00 (0.06) | 0.12** (0.06) | 0.20*** (0.07) | 0.01 (0.03) | 0.04 (0.06) | 651 |
| Non-respiratory health symptom index | -0.07 [0.99] | -0.00 (0.04) | 0.07* (0.04) | 0.13** (0.05) | 0.01 (0.02) | 0.04 (0.04) | 651 |
| Number of respiratory health symptoms | 1.55 [1.60] | -0.02 (0.06) | 0.06 (0.06) | 0.12 (0.08) | 0.01 (0.03) | 0.07 (0.07) | 651 |
| Respiratory health symptom index | -0.09 [0.88] | -0.01 (0.03) | 0.03 (0.03) | 0.06 (0.04) | 0.00 (0.02) | 0.04 (0.04) | 651 |
| Number of health diagnoses | 0.29 [0.56] | -0.03 (0.02) | -0.01 (0.02) | 0.02 (0.03) | -0.01 (0.01) | -0.00 (0.03) | 651 |
| Health diagnoses index | -0.04 [0.89] | -0.06 (0.04) | -0.01 (0.04) | 0.04 (0.05) | -0.03 (0.02) | -0.00 (0.04) | 651 |
| Non-hospital health expenditures (USD) | 4.17 [7.94] | 0.46 (0.32) | 0.35 (0.31) | 0.09 (0.41) | 0.24 (0.18) | 0.07 (0.36) | 651 |
| Hospital visits in past 30 days | 0.30 [0.55] | -0.01 (0.02) | 0.01 (0.02) | 0.02 (0.03) | 0.00 (0.01) | 0.02 (0.02) | 651 |
| Hospital visit expenditures (USD) | 2.82 [10.14] | 0.26 (0.41) | 0.38 (0.41) | 0.37 (0.53) | 0.19 (0.23) | 0.25 (0.47) | 651 |
| Control for average pollution | | | No | Yes | No | Yes | |

Each row and column cell in columns (2)–(6) is a separate OLS regression. All regressions control for baseline socioeconomic and demographic characteristics. Table A7 and Table A9 present detailed results on symptoms and diagnoses.

Table A18: Correlation between health and mean, median, maximum, and duration of PM2.5 exposure (among non-adopters)

| | Mean SD | Mean (SD) | Median (SD) | Max Hourly Pollution (SD) | Hours Above $100\mu g/m^3$ | N |
|-----------------------------------|-----------------|-----------------|-----------------|---------------------------------|----------------------------------|-----|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hypertension ($>130/80$) | 0.52 [0.50] | -0.01 (0.03) | -0.02 (0.03) | 0.01 (0.03) | -0.00 (0.02) | 290 |
| Blood oxygen | 96.58 [2.59] | 0.28* (0.16) | 0.21 (0.15) | 0.33* (0.17) | 0.16* (0.09) | 290 |
| Number of health symptoms | 2.82 [2.96] | 0.00 (0.16) | 0.07 (0.15) | 0.19 (0.17) | 0.03 (0.09) | 291 |
| Health symptoms index (z-score) | 0.02 [1.02] | 0.00 (0.06) | 0.02 (0.05) | 0.07 (0.06) | 0.01 (0.03) | 291 |
| Number of health diagnoses | 0.31 [0.59] | -0.01 (0.04) | -0.01 (0.03) | 0.02 (0.04) | 0.00 (0.02) | 291 |
| Health diagnoses index | 0.01 [1.00] | -0.05 (0.06) | -0.06 (0.06) | 0.02 (0.06) | -0.01 (0.03) | 291 |
| Hospital visits in past 30 days | 0.35 [0.59] | 0.00 (0.04) | -0.02 (0.03) | 0.03 (0.04) | -0.00 (0.02) | 291 |
| Hospital visit expenditures (USD) | 3.41 [10.94] | 0.50 (0.65) | 0.18 (0.61) | 0.95 (0.70) | 0.27 (0.36) | 291 |

Each row and column cell in columns (2)–(5) is a separate OLS regression. All regressions control for baseline socioeconomic and demographic characteristics. Hypertension refers to stage 1. [Table 5](#) present the same for the entire sample.

Table A19: Correlation between health and mean, median, maximum, and duration of PM2.5 exposure (among adopters)

| | Mean SD | Mean (SD) | Median (SD) | Max Hourly Pollution (SD) | Hours Above $100\mu g/m^3$ | N |
|-----------------------------------|-----------------|-----------------|-----------------|---------------------------------|----------------------------------|-----|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hypertension (>130/80) | 0.50 [0.50] | 0.04 (0.03) | 0.02 (0.03) | 0.03 (0.03) | 0.01 (0.02) | 355 |
| Blood oxygen | 96.84 [2.30] | -0.12 (0.14) | 0.00 (0.15) | -0.27** (0.12) | -0.14* (0.08) | 355 |
| Number of health symptoms | 2.27 [2.38] | -0.07 (0.14) | -0.12 (0.14) | 0.14 (0.12) | 0.01 (0.08) | 360 |
| Health symptoms index (z-score) | -0.18 [0.83] | -0.03 (0.05) | -0.06 (0.05) | 0.05 (0.04) | 0.00 (0.03) | 360 |
| Number of health diagnoses | 0.28 [0.54] | -0.04 (0.03) | -0.00 (0.03) | -0.02 (0.03) | -0.02 (0.02) | 360 |
| Health diagnoses index | -0.09 [0.79] | -0.07 (0.05) | -0.01 (0.05) | -0.04 (0.05) | -0.04 (0.03) | 360 |
| Hospital visits in past 30 days | 0.26 [0.51] | -0.02 (0.03) | -0.01 (0.03) | 0.00 (0.03) | 0.01 (0.02) | 360 |
| Hospital visit expenditures (USD) | 2.34 [9.43] | -0.18 (0.60) | -0.46 (0.62) | -0.01 (0.53) | 0.04 (0.33) | 360 |

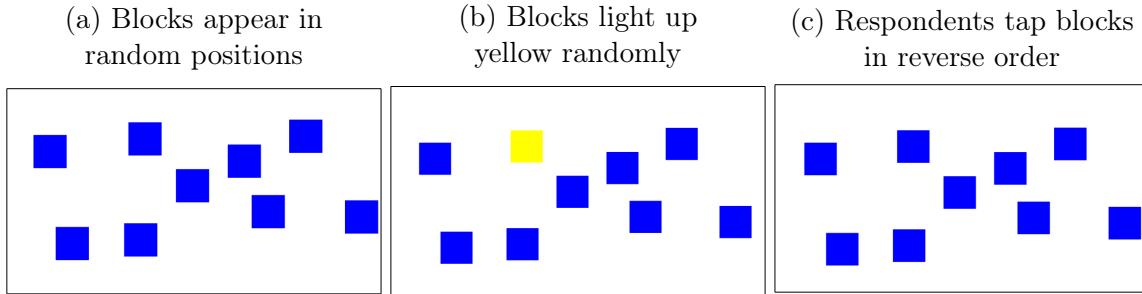
Each row and column cell in columns (2)–(5) is a separate OLS regression. All regressions control for baseline socioeconomic and demographic characteristics. Hypertension refers to stage 1. [Table 5](#) present the same for the entire sample.

C Cognitive assessments

C.1 Reverse Corsi Block

Implementation of the Reverse Corsi Block task follows Brunetti et al. (2014). For each trial, nine blue blocks appear in random locations on the screen. They take turns lighting up. Respondents are then asked to tap the blocks in reverse order of how they lit up (see Figure A6). For each element in the sequence, if the respondent taps on the correct block, it turns green and the respondent can proceed to tap the next block in the sequence. If the respondent taps any other block, it flashes red and the respondent moves to the next trial. The first trial sequence contains two elements. For each sequence the respondent gets completely correct, the sequence length increases by one.

Figure A6: Corsi Stimuli



Note: This figure shows the three stages of the reverse Corsi blocks test. The test is designed to measure working memory. First nine blocks appear in random positions. They then light up in a random sequence. Respondents must then tap the blocks in the reverse order of how they lit up. After each correct trial, the length of the sequence increases by one, and after every incorrect trial, the length of the sequence decreases by one down to a minimum of two elements.

C.2 Hearts and Flowers

Implementation of the Hearts and Flowers task follows the “dots” task outlined by Davidson et al. (2006). Respondents see a fixation dot in the center of their screen with blue boxes on the left and right. Respondents then see a sequence of hearts and flowers appear on the boxes. For each trial, respondents must press either the “Q” or “P” key. When a heart appears, respondents must press the key on the same side as the heart. While when a flower appears, respondents must press the key on the opposite side (see Figure A7).

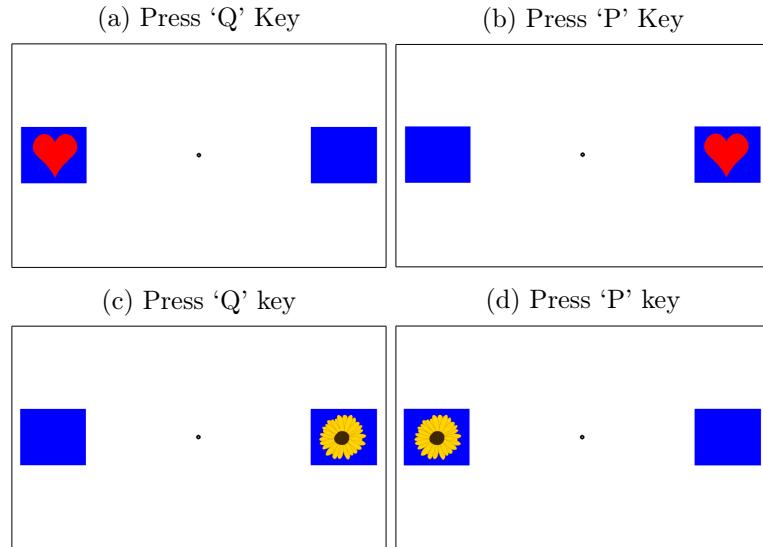


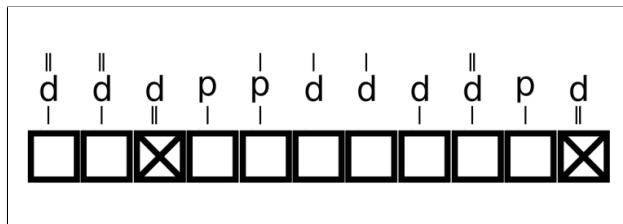
Figure A7: Hearts and Flowers Possible Stimuli and Responses

Note: The figure shows the four possible stimuli and responses for the hearts and flowers test. The test is designed to assess inhibitory control. Respondents see a series of hearts and flowers appear on the blocks. When a flower appears, the respondent must press the key on the opposite side of the keyboard. When a heart appears, the respondent must press the key on the same side of the keyboard.

C.3 d2 Attention Task

The d2 task follows the general instructions outlined in Bates and Lemay Jr. (2004) and Brickenkamp and Zillmer (1998). For each trial, eleven letters (either p or d) appear on the screen with between zero and two dashes above and zero and two dashes below for a total number of dashes between zero and four (see Figure A8). The respondent's job is to mark all of the d's with a total of two dashes by tapping the box below the letter. After 5106 ms, the trial ends. Until that time has elapsed, respondents can un-mark and re-mark letters as they please. Another set of eleven letters appears after 500 ms.

Figure A8: d2 Stimuli



Note: The figure shows an example of a trial from the d2 test. The test is designed to assess attention. Respondents see a series of d's and p's with up to two lines below and above. They must tap the boxes below all d's with a total of two dashes before the trial ends.