

Exposure-enhanced goods and technology disadoption*

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Abstract

Policymakers often subsidize goods that generate positive externalities, only to see these goods disadopted. We posit that disadoption can be mitigated by incentivizing longer exposure, which reduces disadoption via three mechanisms: information, taste, and ability. We develop a theoretical model with these mechanisms and validate the model's predictions using a field experiment in which a household's period of exposure to water-efficient technologies was exogenously manipulated. Using our model, we develop intuition about the optimal time distribution of subsidies. We show that limited-duration exposure subsidies can outperform subsidies offered at the point of purchase or in perpetuity conditional on use.

Keywords: Disadoption, Randomized Controlled Trial, Habit Formation, Learning by Doing, Experience Goods

JEL Codes: D12, D91, H23, O23

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1 Introduction

Many public policy problems have technical solutions. Widespread use of insecticide-treated bednets can reduce the transmission of malaria (Lengeler 1998). Switching from incandescent to compact fluorescent lightbulbs can reduce greenhouse gas emissions (Allcott and Taubinsky 2015). Adopting conservation agriculture practices can reduce environmental damage from industrial agriculture (Kassam et al. 2014). Switching from traditional biomass cookstoves to improved cookstoves can improve public health and reduce deforestation (Ruiz-Mercado et al. 2011).

Although governmental and nongovernmental organizations expend substantial resources to encourage people to adopt these technologies, people often subsequently disadopt them. One year after a pair of anti-malarial insecticide-treated bed nets were distributed for free to households in Uganda, approximately 55 percent of recipient households did not own one anymore (Clark et al. 2016). Among households that received free electricity-conserving compact fluorescent lamps in Kenya, 63 percent were no longer using a CFL approximately four years later (Figueroa 2016). Most farmers in Ghana, South Africa, and Zambia “quickly” reverted to former crop management practices after development and research projects temporarily induced high take-up of practices associated with Conservation Agriculture (Giller et al. 2009). In a randomized trial that offered improved cookstoves to more than 2000 households in India, 32 percent of households *destroyed* the improved stove within four years (Hanna, Duflo, and Greenstone 2016). None of these technologies was displaced by a superior technology—people simply reverted to a prior technology or practice.

Mitigating disadoption is thus important for applying technical solutions to policy problems. Although the adoption of these solutions has received a lot of attention from scholars, disadoption—or, conversely, the persistence of adoption decisions—has received far less attention (exceptions include Nourani (2017), Carter, Laajaj, and Yang (2021), Hussam et al.

(2022), Giller et al. (2009), Hanna, Duflo, and Greenstone (2016), Figueroa (2016), and Clark et al. (2016)). For example, although disadoption is common in environmental, health, and development contexts, it is never mentioned in a widely cited review on the microeconomics of technology adoption (Foster and Rosenzweig 2010).

We posit that the incentives to disadopt many pro-social goods—i.e. goods with positive externalities—decrease with increasing exposure to the goods. We say a good is “exposure-enhanced” if past use of the good raises the expected net benefit of using the good. Exposure can raise the expected net benefit via three mechanisms. First, using a good can provide *information* about the good or the match quality with the person using it (Nelson 1970). Second, using a good can strengthen the person’s *taste* for using the good (Becker and Murphy 1988). Third, using a good can improve the person’s *ability* to use the good (Foster and Rosenzweig 1995). Information, taste, and ability are *exposure-enhancing mechanisms*.

Using a randomized field experiment, we provide empirical evidence that these exposure-enhancing mechanisms can be leveraged to reduce the disadoption of a pro-social good. Then, using a theoretical model, we demonstrate that, in the presence of these mechanisms, exposure subsidies—subsidies that extend beyond the point of adoption but do not last forever—can be better than one-time adoption subsidies or perpetual use subsidies. In the process of building this model, we clarify the concepts and terminology from several branches of the economics literature that study goods for which exposure can increase the perceived net benefit of use.

In the randomized field experiment, plumbers installed low-flow water fixtures in 870 households in May and June 2015 in the arid Guanacaste province of Costa Rica. Exposure to the technologies was experimentally varied by randomly offering some households a cash bonus conditional on the water-conserving technologies remaining in place four months after installation (i.e., an exogenous source of variation in exposure). We estimate that 87 percent

of the difference in technology use observed after four months persisted for at least a year after the exposure subsidy was no longer being offered.

The primary experimental results do not allow us to disentangle the three exposure-enhancing mechanisms. However, we are able to use supplementary data from household surveys and from administrative records of water consumption to explore which exposure-enhancing mechanisms were operative in our study context. In support of the information mechanism, we estimate that the average household saved money on their water bills after adopting the technologies (around 6%) and that the bonus recipient group perceived higher savings than the no-bonus group. In support of the taste mechanism, households in the bonus group were around 10 percentage points more likely than households in the no-bonus group to report preferring the low flow showerhead and low flow kitchen faucet to the status quo technologies. Survey responses do not support the hypothesis that households became better at using or maintaining the technologies. Thus the analysis suggests that the information and taste mechanisms were active but the ability mechanism was not.

In our theoretical model, we explore the implications of exposure-enhancing mechanisms for the design of the optimal subsidy for encouraging the adoption of pro-social goods. In policy discussions of such goods, attention tends to gravitate towards Pigouvian subsidies—subsidies with the same magnitude as the externality—offered at the point of purchase or offered in perpetuity conditional on use. This attention is understandable because Pigouvian subsidies elegantly incorporate externalities into individual decision-making (Baumol 1972). However, several common features of policy contexts—administrative costs, present bias, and liquidity constraints—affect the optimal timing of subsidy payments. Simple Pigouvian subsidies, equal in magnitude to the size of the externality and offered in perpetuity conditional on use, are not optimal in the presence of those features. Exposure-enhancing mechanisms also disrupt the optimality of simple Pigouvian subsidies. We derive optimal

subsidies that adjust for these features, and we show that exposure subsidies—subsidies that extend beyond the point of purchase but do not last forever—can be better than purchase subsidies or subsidies offered in perpetuity conditional on use.

This paper contributes to the large literature on technology adoption (Foster and Rosenzweig 2010) and the relatively small, related literature focused on the challenge of disadoption. Many public policy problems appear to have low-cost technical solutions that are not widely used (Allcott and Taubinsky 2015; Kassam et al. 2014; Lengeler 1998; Ruiz-Mercado et al. 2011; Berkouwer and Dean 2019). Even when there is initial uptake of the innovative good, practice, or behavior, subsequent disadoption is high—people revert to a prior technology or no technology after having used the new technology (Figueroa 2016; Giller et al. 2009; Clark et al. 2016; Hanna, Duflo, and Greenstone 2016). Thus, to achieve public policy goals, economists need to understand the processes of both technology adoption and disadoption.

The disadoption literature is distinct from the much larger literature on technology adoption. Much of the literature on technology adoption imagines technology as an unambiguous advance from what came before it and an inevitable link to what will come after it. In that framework, people cease using a technology because it is replaced by a superior technology (e.g. Dinar and Yaron (1992) and Abera (2008)). That contrasts with our framework, in which disadoption occurs because a firm or household reverts to a previous technology or to the absence of technology. In the diffusion of innovations literature, this is called “disenchantment discontinuance” (Rogers 2002).

This paper also contributes in two ways to the broader economic literatures on habit formation, learning-by-doing and experience goods. First, in the process of building our model, we clarify and show the connections between the concepts and terminologies from these disparate branches of the economics literature. At their core, these literatures explore goods for

which exposure can increase the perceived net benefit of use. Second, we demonstrate how these literatures connect to the broader public policy question of optimal subsidy design for behaviors that generate positive externalities. Our paper highlights conditions under which policymakers can optimally use short-term incentives to induce long-term behavioral change.

Section 2 introduces a theoretical model defining exposure-enhanced goods. Section 3 describes the context in which the experiment was run. Section 4 describes the design of the experiment. Section 5 presents the results of the experiment. Section 6 builds on the model to develop policy intuition about the optimal time distribution of subsidies. Section 7 concludes.

2 Theory of exposure-enhanced goods

To be precise about the meaning of exposure-enhanced goods and the information, ability, and taste mechanisms, this section introduces definitions and a theoretical model.

A good is *exposure-enhanced* if past use of the good raises the expected net benefit of using the good. Introducing this term is useful because it highlights that several mechanisms might be at play when prolonged or persistent use increases the perceived net benefit of using the good, thereby increasing the chances of continued use. Furthermore, although there are some situations where a social planner would want to know which mechanism is operating, there are also situations where knowing the mechanism is not necessary.

The term *good* is also intended to be broadly inclusive. An exposure-enhanced good could be a durable good like a tractor, a non-durable good that is used repeatedly like fertilizer, or a procedure or technique like planting cover crops to reduce soil erosion. Consumption goods, investment goods, intermediate goods, and technologies can all be exposure-enhanced goods.

Our model combines three mechanisms of exposure-enhancement: information, ability,

and taste. First, using a good can provide information, which reveals the quality of the good, the agent's type, or the match quality between the good and the agent. Second, using a good can make the agent better at using the good—e.g. more output is produced with a fixed input of effort. Third, using a good can give the agent a stronger taste for using the good.¹

In the model, an agent chooses in each period whether or not to use a good to maximize the discounted stream of expected utility (or profit). Using the good contributes to a stock of exposure. Ability and taste are both increasing functions of the exposure stock. Marginal utility is increasing in both ability and taste. Using the good also reveals a signal to the agent about match quality between the good and the agent. The impact of the signal on belief about match quality expresses the information mechanism. The discounted stream of expected utility in period t is:

$$\sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} u(r_{t+j}, A(S_{t+j}), T(S_{t+j}), \theta) dF_t(\theta) \quad (1)$$

where $r \in \{0, 1\}$ is a discrete choice to either use the good or not, $S \geq 0$ is an exposure stock, A is ability, T is taste, F is a cumulative distribution function expressing the agent's probabilistic belief about match quality θ , and $\delta \in (0, 1)$ is the agent's time discount factor. We assume that the marginal utility of using the good is weakly increasing in ability, $\frac{\partial^2 u}{\partial r \partial A} \geq 0$, in taste, $\frac{\partial^2 u}{\partial r \partial T} \geq 0$, and in match quality, $\frac{\partial^2 u}{\partial r \partial \theta} \geq 0$.

The exposure stock evolves according to the following law of motion:

$$S_{t+1} = (1 - d)(S_t + r_t) \quad (2)$$

where $d \in (0, 1]$ is a depreciation parameter.

¹Hussam et al. (2022) use different language to describe the same three mechanisms and focus exclusively on what we call the taste mechanism in their theoretical model and empirical investigation.

The agent can observe a signal about match quality but cannot observe past utility.² The population distribution of match quality is $\theta \sim F(\theta)$. If the agent has not used the good prior to period t , then the agent’s belief about match quality is the same as the population distribution, $F_t = F$. If the agent uses the good in period t , then it observes a signal ω_t that depends on its own match quality θ_i , $\omega_t \sim G(\omega_t|\theta_i)$, and it updates its belief using Bayes’s rule, forming posterior belief F_{t+1} . If the agent does not use the good, then it does not observe a signal, and its belief is the same in the next period, $F_{t+1} = F_t$.

Relation to terms in prior literature. The exposure-enhancing mechanisms we identify as being potentially useful for mitigating disadoption correspond to three branches of prior literature. The information mechanism is associated with the literature on experience goods (Liebeskind and Rumelt 1989; Villas-Boas 2004; Ching, Erdem, and Keane 2013; Ching, Erdem, and Keane 2017), the taste mechanism is associated with the literature on habit formation (Carroll, Overland, and Weil 2000; Hussam et al. 2022), and the ability mechanism is associated with the literature on learning by doing (Foster and Rosenzweig 1995; Van Benthem, Gillingham, and Sweeney 2008; Kverndokk and Rosendahl 2007). The mapping between terms in prior literature and exposure-enhancing mechanisms is summarized in Table 1.

However, a simple mapping can obscure as much as it clarifies. The ability mechanism is usually associated with production by firms, but consumers are certainly capable of learning how to use a good or technology to raise marginal utility. Learning about match quality is usually associated with experience goods consumed by consumers, but firms certainly encounter goods that they must use in order to discern match quality. Formal models with habit formation or learning-by-doing are often isomorphic in the sense that both use exposure stocks to raise marginal profit or utility. Because the labels do not map cleanly to

²If the agent could observe past utility then it would be able to infer match quality. In our model, the signal is the only source of information about match quality.

Table 1: Exposure-enhancing mechanisms

Mechanism	Branches of literature	Description
Information	Experience goods, Consumer learning	Using the good reveals match quality between the user and the good.
Taste	Habit formation	Using the good makes subsequent use more enjoyable (or less unenjoyable).
Ability	Learning by doing	Using the good makes the user better at using the good.

Note: This table describes three mechanisms by which goods can be enhanced by exposure and relates the mechanisms to terminology in prior publications.

the mechanisms, scholars have appropriated the labels to apply to multiple mechanisms. For example, although most of the literature about learning by doing corresponds to what we would call the ability mechanism, some of it also covers what we would call the information mechanism, as in the discussion of match quality in Thompson (2010).

Noting that the mechanisms have the shared feature that spending more time with a technology has the potential to raise the perceived net benefit of using the technology, our framework maintains clarity around three concepts that ought to be distinct. Learning how to use a technology is not the same as learning information about match quality. Exposure that builds competence is not the same as exposure that reveals taste or exposure that transforms taste.

The conceptual distinction between the taste mechanism and the ability mechanism is important even though their formal expression is similar. Following prior literature on habit formation and learning by doing, the formal model we present expresses the two mechanisms isomorphically; both are represented by the influence of a stock of exposure on period utility. It would be easy to separate these two mechanisms into a utility component for the taste mechanism and a productivity component for the ability mechanism. We express these

components jointly for simplicity and note that the model can be applied to situations with one or both mechanisms.

To be clear, we do not claim that all technologies are enhanced by exposure. Each of the three mechanisms may or may not be present for any particular good. For example, Orgill-Meyer et al. (2019) report that, as part of a sanitation campaign, a randomly assigned intervention temporarily boosted ownership of household latrines but had no long-run impact after 10 years. If any of the mechanisms were present for household latrines, they were not strong enough to impact behavior at that time horizon. More research is needed to characterize which technologies have their perceived benefits enhanced by exposure.

In order to disadopt a good, a person must have previously adopted it. In our terminology, using a good once counts as adopting it, but in some prior literature using a good once does not count as adopting it. Lehmann and Parker (2017) define disadoption as “the voluntary cessation of a valued and adopted behavior done with the intent that the cessation be permanent.” Our concept of disadoption is broader because it includes goods that are used only for a short time, even just for a trial period.

Relation to prior models. We contend that exposure-enhancing mechanisms can be harnessed to mitigate disadoption. The idea that short-term subsidies might induce long-term changes in behavior is not new. Most prior literature examining the impact of short-term subsidies on long-term behavior change presents theory tailored closely to the particular policy context, e.g. Carter, Laajaj, and Yang (2021) and Kverndokk and Rosendahl (2007). These models typically incorporate intertemporal complementarities (i.e. exposure-enhancing mechanisms) without articulating the sources of the complementarities.

Among general models that are not tailored closely to a particular context, ours is unique in examining dynamic extensive margin decisions with all three exposure-enhancing mechanisms. Our model bears some resemblance to the model of addiction in Gruber and Köszegi

(2001) through dynamic extensive margin decisions and the presence of an exposure stock, but they are unconcerned with match quality and impose an additional “tolerance” property of addictive goods. Although we focus discussion of our model on a binary choice where using the good generates a positive externality, our argument about the timing of subsidies also applies when failing to use the good generates a negative externality (López 2016). Ghadim and Pannell (1999) motivate a model of crop adoption with both the information and the ability mechanisms with a focus on either static extensive margin decisions or dynamic intensive margin decisions, not dynamic extensive margin decisions. Oliva et al. (2020) examine takeup and disadoption in the presence of uncertainty, and their model is a special case of ours with only two periods and only the information mechanism.

A common concern when policymakers contemplate subsidies for health and development goods is that subsidy recipients will anchor on the subsidized price (Cohen and Dupas 2010). Dupas (2014) models anchoring alongside the information mechanism, but without the taste or ability mechanisms. Both (Cohen and Dupas 2010) and Dupas (2014) present empirical evidence that anchoring does not reduce future willingness to pay in the context of anti-malarial bednets. We do not model anchoring.

In the next three sections, we describe the context, design, and results of a controlled field experiment that demonstrates that incentivized exposure to a good can have a persistent causal impact on subsequent use.

3 Background

Development and environmental projects frequently include the promotion of goods, behaviors, and practices that would be beneficial if adopted widely but also suffer from widespread disadoption.

The AC3 Project. In 2013, the Tropical Agricultural Research and Higher Education

Center (CATIE) set out to improve the capabilities of water management organizations in Central America to adapt to climate change as a part of the AC3 project (abbreviation of the Spanish for “Water Communities and Climate Change”). One component of the AC3 project was the randomized controlled trial reported in this paper, which was implemented in a dry region of Costa Rica subject to seasonal droughts. As a consequence of climate change, local temperatures are predicted to increase and precipitation is predicted to decrease, exacerbating what is already an acute global crisis in groundwater management (Famiglietti 2014; Imbach et al. 2015).

Water prices. Water systems in rural communities of low- and middle-income nations are often managed by volunteer councils called community-based water management organizations (CBWMOs). In Costa Rica and elsewhere, CBWMOs cannot easily change the quantity of water available for the local water supply, and thus mitigating water system stress typically requires managing demand. A prominent tool for managing demand is variable pricing for water consumption. The national public utility regulator in Costa Rica sets a national price schedule, including a fixed price per month and a marginal price per cubic meter, that CBWMOs are encouraged to implement. The national price schedule is set below marginal cost because of concerns about access by low-income households. More than half of the CBWMOs in the study region charged prices lower than the national price schedule.

In this regime where water prices are below marginal costs, water consumption generates a negative externality. When concerns about equity restrict the extent to which price is used as a tool for managing this externality, policymakers look for technological solutions such as water-conserving technologies (Renwick and Archibald 1998). By reducing demand on regional water systems, the use of water-conserving technologies generates a positive externality.

Low-flow water technologies. Households were offered low-flow water fixtures with

free installation. A subset of households were offered a cash bonus for continuing to use the fixtures for a certain period of time. Low-flow fixtures were not available commercially in the communities in the experiment, so households did not have previous access to or exposure to the fixtures. There was also no evidence of a secondary market for the low-flow fixtures supplied for the experiment.

There are several technologies for reducing water consumption. Flow restriction limits the throughput of a pipe, reducing the maximum flow rate of water. Aeration adds air to water coming through a pipe, which has the same consequence of reducing the maximum flow rate of water and also affects the composition of water and air below the maximum. The experiment distributed faucet aerators, which use aeration only, as well as low-flow showerheads, which use both flow restriction and aeration. We use the term low-flow fixtures to include both faucet aerators and low-flow showerheads.

The AC3 project began with an intent to distribute low-flow fixtures to households. During the planning phase, the AC3 team consulted with engineers about the possibility that households would disadopt the low-flow technologies. Engineers claimed that if households disadopted the technologies, it would be because the households had not “spent enough time” using them. This claim was an inspiration for the bonus treatment arm and for the theoretical model that formalizes how exposure can affect subsequent use. We explain below how the exposure-enhancing mechanisms modeled in [section 2](#) may have manifested in the context of low-flow fixtures.

The information mechanism could have been active if the households learned about their idiosyncratic costs or benefits by using the fixtures. Alpízar, Bernedo, and Ferraro (2021) estimate that the low-flow fixtures used in the experiment reduced water use by an average household by approximately seven cubic meters per month. Households had access to information about their cost savings by observing their water bills with the technology

installed.

The taste mechanism could have been active if households habituate to low-flow fixtures over time. Low-flow fixtures change the tactile feeling of using water, which can be unpleasant for new users. However, after using the fixtures for several months, households may grow accustomed to the new feel and feel less displeasure or even start enjoying the new sensation.

The ability mechanism could have been active if households learned how to use the fixtures more effectively. Two opportunities for learning are in cleaning the fixtures and in knowing when to use alternative spouts. Water supplied by water systems in this region of Costa Rica often has particulates that accumulate in low-flow fixtures. Muck needs to be cleaned out occasionally, so it is possible that households that were incentivized to keep the technology installed learned how to clean the muck rather than disadopting at the first sign of seriously impeded flow. Removing the low-flow fixtures does not require specialized tools or expertise—households that wanted to remove a fixture would have been capable of doing so without hiring a plumber. The other opportunity for enhancing ability is learning when not to use the low-flow fixtures. For example, if a pot of water with a fixed quantity is needed then households may have learned to detach the aerator occasionally or to use an alternative spout without a low-flow fixture in order to save time.

4 Experimental design

We use a randomized controlled trial to demonstrate that exposure to a good can have a persistent causal impact on subsequent use in the context of resource-conserving technology. Households were offered the opportunity to receive free low-flow water fixtures. A subset of households was randomly assigned to be offered a cash bonus if the technology was still in use during an audit four months after installation. One year after the initial audit, the field team conducted a second, unincentivized and unannounced audit. We use random assignment to

the cash bonus as an instrument to estimate the causal effect of four months of exposure on subsequent use after the bonus is no longer offered.³

The experiment was designed to test the common feature of the exposure-enhancing mechanisms, not to distinguish among the three exposure-enhancing mechanisms. We supplement the primary experimental results with survey data and administrative data to explore which exposure-enhancing mechanisms were operative.

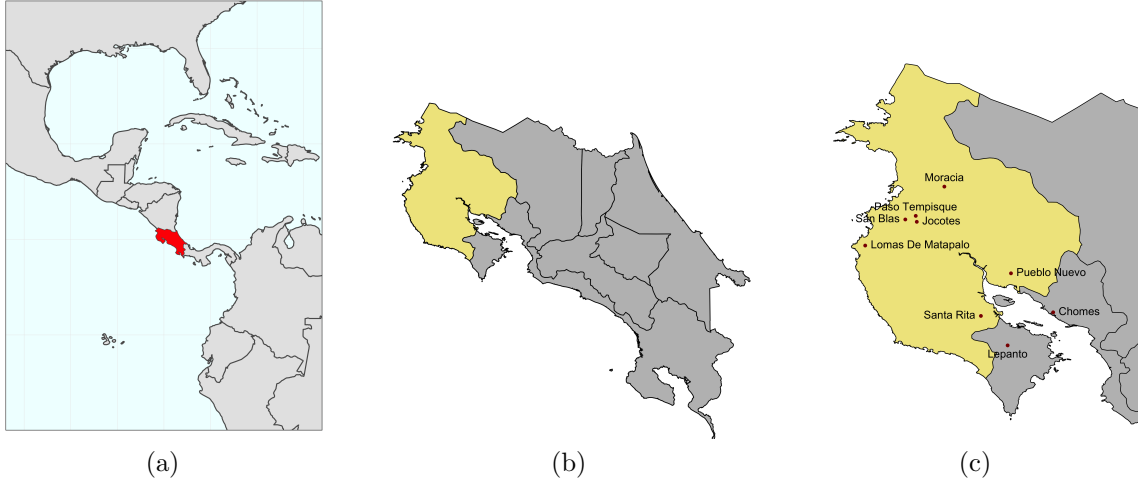
4.1 Sample

The sample consists of households that were recruited from nine small, rural, low-income communities in the dry corridor of Costa Rica. The nine communities, mapped in Figure 1, met the following selection criteria: (1) The community’s water was managed by a community-based water management organization. (2) The CBWMO charged households volume-based marginal prices for water use. (3) The CBWMO was willing and able to provide the research team with monthly household-level water use records back to 2013. (4) The CBWMO agreed that random assignment could be used to determine whether households would receive water-efficient technology. Appendix Table E.1 reports water prices and the number of households in the sample for each of the nine communities.

In May and June 2015, four installation teams knocked on doors in the nine communities to recruit households for the experiment, conduct a pre-treatment survey, and install the technology. Each installation team consisted of one interviewer and one plumber. Visits were conducted using a tablet that allowed the interviewer to show participants a video of low-flow water fixtures and explain the individual benefits of lower water bills and environmental benefits of conserving water. Of 1898 households targeted, installation teams made contact with an adult decision-maker in 1346 households, and 1310 households agreed to participate

³The experiment is not pre-registered. It was designed in 2014 and implemented 2015, prior to the authors becoming aware of the importance of pre-registration.

Figure 1: Map of communities in experiment



Note: Households were located in nine communities in the dry corridor of Costa Rica. Panel (a) depicts Costa Rica shaded red with marked borders of surrounding countries. Panel (b) depicts the Guanacaste Province shaded yellow with marked borders of other provinces in Costa Rica. Panel (c) depicts the nine communities in the experiment, all of which are in or near Guanacaste.

in the experiment and allow installation of the water-efficient technology if they were selected for installation.

Sample households had low education levels and low incomes. Of heads of household in the sample, 81% completed primary school and 27% completed secondary school. Average household monthly income in the sample was around 234,000 CRC (\$440 per month). The average monthly water bill was 7,400 CRC (\$13.93), so household water expenses were on average approximately 3% of household income. Awareness of the impacts of climate change in this population is low, but the environmental benefits of conserving water were explained by the installation teams.

4.2 Random assignment, intervention, and data gathering

Interviewers explained and conducted the random assignment procedure among the households that were willing to install the technologies. A member of the household drew one of three colored chips from an opaque bag. Red chips corresponded to receiving the technology

and the bonus, blue chips corresponded only to receiving the technology, and white chips meant no technology. If the resident drew either a red chip or a blue chip, then the interviewer explained that the household was selected to receive the technology and that the field team would return to ask about the household’s exposure to the technology. If the chip was red, then the interviewer also informed the household that it would be paid a bonus of 20,000 colones (approximately \$38) if the technologies were still installed on the next visit from the field team, which would take place in the next six months. After the random assignment, the plumber immediately attempted to install the technology in as many fixture locations as possible. Prior to installation, some showerhead locations were open pipes, but if there was previously a showerhead present then the plumber removed the old showerhead from the household. Households in both the bonus group and the no-bonus group were told that the field team would return to ask about the household’s experience with the technology within six months, but they were not given an exact date.

The outcome of the randomization was that 438 households received the technology and were offered a bonus, 432 households received the technology without being offered a bonus, and 440 households did not receive the technology. This paper focuses on the comparison between the bonus (treatment) group and the no-bonus (control) group, both of which received the technology, to examine exposure-enhancing mechanisms and technology disadoption.⁴ Note that households in both the bonus group and the no-bonus group were told that the field team would return, so both groups could be influenced by pro-social preferences to avoid disappointing CATIE staff. Only the bonus group could be influenced by a desire to receive the subsidy payment. The subsidy payment was 20,000 CRC (\$38), which was around 9% of monthly household income, or three times as large as a monthly

⁴Alpízar, Bernedo, and Ferraro (2021) use the comparison between the two treatment arms that received the technology and the one treatment arm that did not to examine the effect of low-flow fixtures on water use. The randomized controlled trial on which both papers rely is registered through the American Economic Association registry with RCT ID AEARCTR-0007158.

water bill.

The field team conducted two subsequent audits of households in both groups, the bonus group and the no-bonus group. The first audit was approximately four months after installation, still in calendar year 2015, and the bonus was paid during that visit. The second audit was in 2016, approximately one year after the first audit. Both audits recorded which fixtures still had the water-efficient technology installed.

4.3 Baseline characteristics and balance

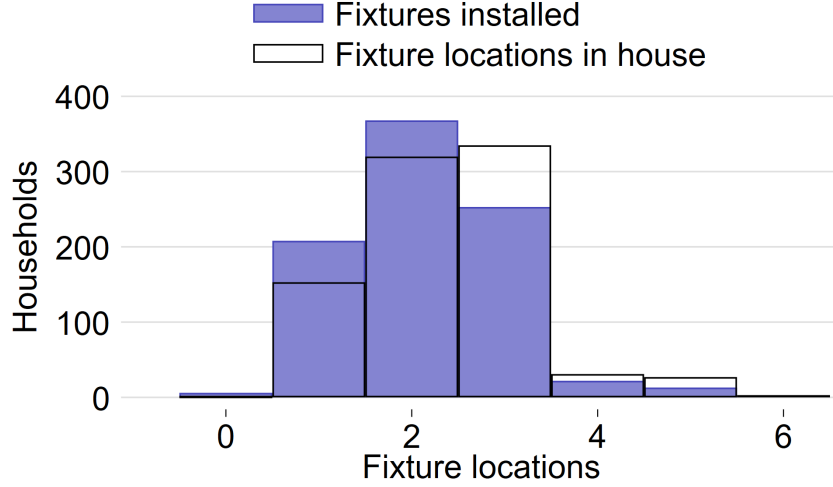
The pre-treatment survey was administered immediately prior to random assignment and installation of the water-conserving technology. Appendix Table E.2 presents summary statistics on household characteristics by treatment assignment. The differences in means between the treatment and control groups are small and, for most characteristics, not statistically different from zero.

4.4 Estimation strategy

The analysis is conducted at the fixture-location level. Each household was offered low-flow fixtures—kitchen faucets, bathroom faucets, and showerheads. As long as the household had a fixture location available, an attempt was made to install the low-flow fixtures. Figure 2 shows that most households had two or three fixture locations available.

We estimate the treatment effect using a two stage least squares regression that uses the randomly assigned bonus offer as an instrument for exposure. Figure 3 illustrates the estimation strategy with a causal graph. Exposure is defined here as *using the technology through the first audit*. The first stage regression is $d_{ij} = \alpha_0 + \alpha_1 z_j + u_{ij}$, and the second stage regression is $y_{ij} = \beta_0 + \beta_1 \hat{d}_{ij} + \epsilon_{ij}$, where z_j is an instrument equal to one if household j was offered a cash bonus and zero otherwise, d_{ij} is a treatment indicator equal to one if

Figure 2: Success of initial installation

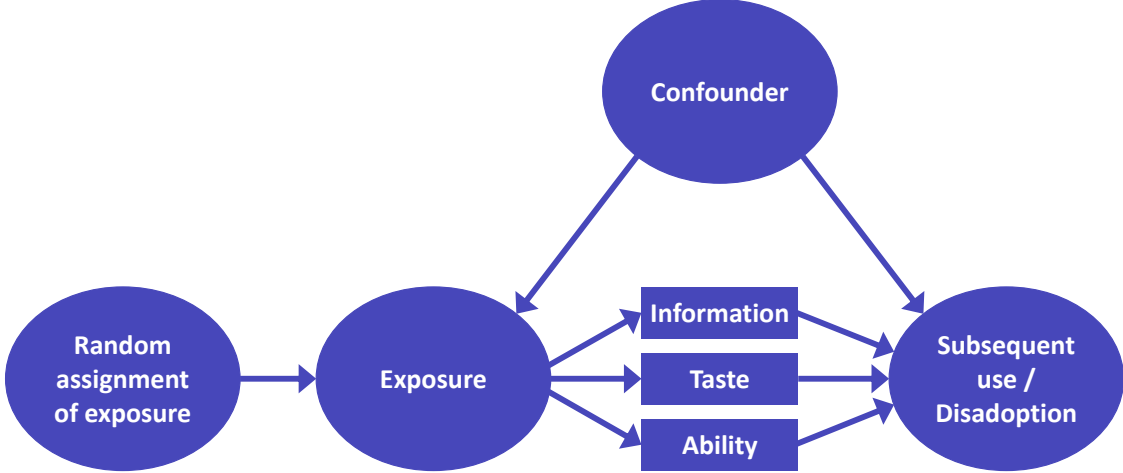


Note: Fixtures were installed in up to six locations: two kitchen faucets, two bathroom faucets, and two showerheads. Most households had between 1 and 3 fixture locations available and between 1 and 3 low-flow fixtures installed. Low-flow fixtures were installed in 89% of fixture locations available and in at least one fixture location in 99% of households.

the household had the technology in place at fixture location i during the 2015 audit and zero otherwise, \hat{d}_{ij} is the predicted value of d_{ij} from the first stage, and y_{ij} is an outcome indicator equal to one if the household had the technology installed at the fixture location during the 2016 audit and zero otherwise.

The coefficient of interest is β_1 , which is the complier average causal effect. This effect can be defined using the potential outcomes framework. A complier is a household's fixture location that is in use at the first (2015) audit (treated; $d_{ij} = 1$) if and only if the household was offered a bonus (assigned to the treatment group; $z_j = 1$). The complier average causal effect is the difference between the outcome if the complier fixture location were treated ($y_{ij}|d_{ij} = 1$) and the outcome if the complier fixture location were untreated ($y_{ij}|d_{ij} = 0$), where the outcome is subsequent use during the second (2016) audit.

Figure 3: Causal graph



Note: We estimate the causal effect of exposure on retention, using random assignment as an instrument for exposure. We posit that information, taste, and ability are the channels by which exposure affects retention.

5 Experimental results

In this section, we estimate the complier average causal effect of exposure to a resource-conserving technology on subsequent use of the technology.

Among households that were present in both audits, the cash bonus induced greater exposure in the treatment group than in the control group. Table 2 shows that during the 2015 audit the fraction of low-flow fixtures in use in bonus treatment households was 6.2 percentage points higher than in no-bonus control households—84.1% of low-flow fixtures were in use in the treatment group and 77.9% in the control group. The gap in use during the 2015 audit indicates correlation between the instrument (cash bonus) and the treatment (exposure).

A year after the cash bonus was no longer being offered, the treatment group was still using low-flow fixtures at a higher rate than the control group. Table 2 shows that during the 2016 audit the fraction of low-flow fixtures in use in bonus treatment households was 4.5 percentage points higher than in no-bonus control households—64.0% of low-flow fixtures

Table 2: Summary of results

	Low-flow fixtures in use					
	No-bonus control		Bonus treatment		Full sample	
	Count	%	Count	%	Count	%
Treatment assignment	829	100.0	937	100.0	1766	100.0
Installation	720	86.9	826	88.2	1546	87.5
2015 audit	646	77.9	788	84.1	1434	81.2
2016 audit	493	59.5	600	64.0	1093	61.9

Note: This table summarizes results for all fixture locations that remained in the sample for both audits.

were in use in the treatment group and 59.5% in the control group. The gap in use between the treatment and control groups during the 2016 audit is a measure of the intention-to-treat effect of the cash bonus.

Most of the gap during the first audit between the treatment and control groups persisted to the second audit. The gap during the 2016 audit (4.6 percentage points) was 74% as large as the gap during the 2015 audit (6.2 percentage points). If households that were successfully audited were representative of households that were assigned to treatment, then the fraction of the gap during the 2015 audit that persisted to the 2016 audit is an unbiased estimator of the treatment effect of exposure on subsequent use. Column 1 of Table 3 shows the estimated treatment effect (74%) as a coefficient in a two stage least squares regression.

Column 2 of Table 3 shows that the estimated treatment effect adjusted for community-level fixed effects is 82%. We report the robust test for weak instruments proposed by Olea and Pflueger (2013) and implemented by Pflueger and Wang (2015). Because instruments are weak in several of our specifications, we also report Anderson-Rubin confidence sets that are robust to weak instruments for all specifications (Anderson and Rubin 1949; Finlay, Magnusson, and Schaffer 2014).⁵ The confidence sets rule out a zero effect for all specifications that adjust for community-level fixed effects.

⁵Our approach to instrument strength follows Andrews, Stock, and Sun (2019).

Table 3: Effect of exposure on subsequent use of low-flow fixtures, 2SLS estimates

	(1)	(2)	(3)	(4)	(5)
	In use 2016	In use 2016	In use 2016	In use 2016	In use 2016
Exposure	0.739 (0.353)	0.816 (0.320)	0.257 (0.115)	2.623 (0.959)	0.868 (0.327)
Observations	1,766	1,766	2,076	2,076	1,766
R-squared	0.305	0.328	0.190	-1.892	0.318
Mean of dep var	0.618	0.618	0.634	0.603	0.619
Community FEs		X	X	X	X
Imputation/weight			LB	UB	PW
MP F-stat	8.663	10.025	69.991	5.781	10.865
MP tau=20% CV	15.062	15.062	15.062	15.062	15.062
AR chi-squared	2.975	4.463	4.274	20.429	4.780
AR p-value	0.085	0.035	0.039	0.000	0.029
AR confidence set	[-0.170,1.677]	[0.094,1.689]	[0.016,0.471]	[1.445,.]	[0.155,1.814]

Standard errors in parentheses

Note: This table presents estimates of the complier average causal effect of exposure to low-flow fixtures in 2015 on continued use in 2016. Column 1 is unweighted two-stage least squares. Column 2 adds community-level fixed effects. Column 3 replicates column 2 using imputed values in order to calculate a lower bound estimate. For the 2015 audit, households with missing values assigned to the treatment group are assumed to be treated and households assigned to the control group are assumed to be untreated (widening the exposure gap). For the 2016 audit, households with missing values are assumed to be using the low-flow fixtures (narrowing the subsequent use gap). Column 4 replicates column 2 with imputed values to calculate an upper bound estimate: For the 2015 audit, households with missing values are assumed to be treated (narrowing the exposure gap). For the 2016 audit, households with missing values assigned to the treatment group are assumed to be using the low-flow fixtures, and households assigned to the control group are assumed not to be using the low-flow fixtures (widening the use gap). Column 5 weights observations according to the inverse probability of remaining in the sample, as estimated in Table 4 Column 4. Standard errors are clustered at the household level. The table reports Montiel-Pflueger effective F-statistics and critical values. An effective F-statistic below the critical value indicates a weak instrument. The table also reports Anderson-Rubin test statistics and confidence sets. The AR test is a joint test of the estimate (the effect of exposure) and the exogeneity of the instrument (treatment assignment) (Finlay, Magnusson, and Schaffer 2014). The AR confidence set is constructed by inverting the AR test such that values in the confidence set are values for which the null of the AR test would not be rejected.

Attrition from the sample was nontrivial and correlated with treatment assignment. Treatment and outcome data are present for 83.2% of households (see Appendix Table E.3). The remaining 16.8% of households were missing from one or both audits. Households that were offered a bonus were 8.5 percentage points more likely to be present for both audits than households not offered a bonus. Differential attrition by treatment assignment is a sign

that attrition was nonrandom, and estimators that rely only on households that remain in the sample are potentially biased.

In the presence of attrition, estimating the treatment effect requires making untestable assumptions about unobserved households. If treatment and outcome data are missing at random, then estimators based on the subset of households that are fully observed are unbiased. However, if there is selective attrition—i.e. households with certain characteristics or behavior were more likely to be observed in audits—then estimators based on fully observed households are potentially biased.

We address attrition using two approaches: (1) bounding the treatment effect with conservative assumptions about selective attrition, and (2) applying regression weights based on the estimated probability that a household was present in both audits.

Bounding. To obtain a lower bound on the estimated treatment effect, we make the following imputation assumptions: (LB1) for fixture locations that were not observed in the 2015 audit, treatment status is equal to treatment assignment, i.e. a fixture location was in use if and only if the household was offered a cash bonus, and (LB2) all fixture locations that were not observed in the 2016 audit were in use. To obtain an upper bound on the estimated treatment effect, we make the following imputation assumptions: (UB1) all fixture locations that were not observed in the 2015 audit were in use, and (UB2) for fixture locations that were not observed in the 2016 audit, a fixture location was in use if and only if the household was assigned to the treatment group.

Column 3 of Table 3 shows that, under the lower bound assumptions, we can rule out a null effect of exposure on subsequent use. The effective F statistic exceeds the critical value by a wide margin, rejecting the null of weak instruments. Column 4 of Table 3 shows that, under the upper bound assumptions, the effective F statistic is below the critical value, indicating a weak instrument. In this context, a weak instrument is a consequence of the

gap in exposure between the treatment group and the control group being relatively small. Under the upper bound assumptions, the lower bound of the AR confidence set exceeds one, which we take as a signal that the upper bound assumptions are too weak.

One reason assumptions LB1 and UB1 are conservative is that households in the cash-bonus group were being paid if the technology was installed, so we would expect that there was positive selection into remaining in the sample in the cash-bonus group. In other words, we suspect that audit success was negatively correlated with disadoption in the cash-bonus group, but LB1 and UB1 imply that audit success was positively correlated with disadoption in the cash-bonus group.

Weighting. We apply inverse probability weights to the subset of fixture locations for which we observe both treatment and outcome data. This weighting approach to attrition requires stronger assumptions than were required in the bounding approach; namely, that missingness is random conditional on observable characteristics. The validity of this assumption is supported by the breadth of characteristics we observe and the fact that they have substantial explanatory power for predicting missingness.

Table 4 shows that households with more individuals, households occupied by their owners, and households with long tenure were more likely to remain in the sample. These three predictors are consistent with a story about who was likely to be physically present for an audit—households with more members, and households with longer and stronger connections in the community. Overall, households in the cash bonus treatment were less likely to attrite, which makes sense because they had a financial incentive to remain in the sample during the 2015 audit. Among households assigned to the cash bonus treatment, households in the top income quintile were more likely to attrite, which would be the case if higher income households are less responsive to the cash bonus or less likely to be at home because they have a job.

Table 4: Regression estimates predicting fixture location attrition

	(1)	(2)	(3)	(4)
	Full sample	No-bonus control	Bonus treatment	Full sample
Offered bonus	-0.068 (0.016)			-0.102 (0.017)
# of individuals in household		-0.040 (0.007)	-0.040 (0.007)	-0.039 (0.005)
Owns home		-0.070 (0.033)	-0.070 (0.028)	-0.070 (0.022)
Years in home		-0.004 (0.001)	-0.004 (0.001)	-0.004 (0.001)
Missing income range		-0.023 (0.047)	0.029 (0.038)	0.006 (0.030)
Top income quintile		0.016 (0.033)	0.135 (0.022)	0.020 (0.028)
Bonus X Top income quintile				0.142 (0.038)
Observations	2,076	1,016	1,060	2,076
Pseudo R-squared	0.011	0.074	0.169	0.122
Mean of dep var	0.149	0.149	0.149	0.149

Standard errors in parentheses

Note: This table reports probit regressions that use treatment assignment and household characteristics to predict attrition. A household attrited if it was missing from the 2015 audit or the 2016 audit. Of 870 households in the sample, 152 attrited. Column 1 shows that treatment assignment predicts attrition. Columns 2 and 3 show that household characteristics predict attrition in the no-bonus control group and the bonus treatment group, respectively. Column 4 shows that treatment assignment retains predictive power after adjusting for household characteristics.

Under the assumption that missingness is random conditional on observable characteristics, we estimate a causal effect of exposure on subsequent use of 87%, reported in Column 5 of Table 3. The regression uses inverse probability weights based on predicted values from the regression in Column 4 of Table 4. The effective F statistic indicates a weak instrument, but the Anderson-Rubin confidence set nevertheless rules out a treatment effect of zero.

Thus the experiment provides strong evidence that exposure can mitigate disadoption, as predicted by the model in Section 2. Next, we explore which of the three mechanisms in the model were active in the field experiment. The water billing data and survey data support the activation of an information mechanism and a taste mechanism, but we find no evidence to support the activation of an ability mechanism.

Information. On average, the low-flow fixtures saved households money. Making use of the bonus group, the no-bonus group, and also the no-technology group, Appendix Figure F.1 shows that households with the technology had monthly bills on average around 6% lower than households without the technology (around 450 CRC off of 7400 CRC).

Households that used the technology for longer had more of an opportunity to learn about match quality—how much money the technology was saving them specifically in practice. All else equal, we would expect households with the highest match quality—saving the most money—to be the most likely to continue using the technology. Table 5 shows two survey responses that indicate that households in the bonus group with high match quality were more aware of saving money than households in the no-bonus group with high match quality. First, during the 2015 audit, households in the bonus group were 10 percentage points more likely than households in the no-bonus group to mention saving money as a motive for continuing to use the technology. Second, during the 2016 audit, households in both groups guessed how much they had saved, and guesses in the bonus group were around 300 CRC per month more on average than guesses in the no-bonus group. Both of these differences between the bonus group and the no-bonus group would be expected if more of the households with high match quality in the bonus group realized they were saving money because they had kept the technology in use for longer in order to obtain the bonus.

Taste. After 16 months, households in the bonus group had developed a stronger preference for low-flow fixtures than households in the no-bonus group. Households were asked

Table 5: Survey evidence of exposure-enhancing mechanisms by treatment assignment

Variable	(1) No-bonus control	(2) Bonus treatment	(3) Difference
Information			
Plan to keep because saving money, 2015 audit	0.31 (0.46)	0.42 (0.49)	0.10 (0.04)
Estimated savings, CRC per month, 2016 audit	1427.08 (1324.15)	1714.83 (1372.49)	287.75 (109.10)
Taste			
Prefer bathroom faucet jet with less water	0.92 (0.28)	0.94 (0.24)	0.02 (0.03)
Prefer kitchen faucet jet with less water	0.81 (0.39)	0.90 (0.31)	0.09 (0.04)
Prefer showerhead jet with less water	0.68 (0.47)	0.83 (0.38)	0.15 (0.04)
Ability			
Removed bathroom aerator because low flow requires more time	0.02 (0.14)	0.00 (0.07)	-0.01 (0.01)
Removed kitchen aerator because low flow requires more time	0.05 (0.22)	0.03 (0.16)	-0.03 (0.02)
Removed showerhead because low flow requires more time	0.06 (0.23)	0.03 (0.17)	-0.03 (0.01)
Removed bathroom aerator because broken or clogged	0.09 (0.29)	0.08 (0.27)	-0.01 (0.03)
Removed kitchen aerator because broken or clogged	0.21 (0.40)	0.24 (0.44)	0.03 (0.03)
Removed showerhead because broken or clogged	0.18 (0.39)	0.16 (0.38)	-0.02 (0.03)
Observations	432	438	870

Standard errors in parentheses

Note: The statistics for “Prefer bathroom faucet/kitchen faucet/showerhead jet with less water” are calculated as a fraction of households that expressed a positive or negative preference. The questions that we interpret as being about taste were specifically about the feeling of the water, not a general preference for the presence or absence of the fixture—the survey question used the Spanish word “chorro,” meaning jet or stream. The reasons for removal statistics are calculated as a fraction of households that ever had the technology installed.

during the 2016 audit whether they preferred the jet of the water with or without the new technology. Among households that expressed a preference either for or against the low-flow showerhead, households in the bonus group were 15 percentage points more likely than households in the no-bonus group to prefer the lower flow. Among households that expressed a preference either for or against the low-flow kitchen faucet, households in the bonus group were 9 percentage points more likely than households in the no-bonus group to prefer the

lower flow. Preferences for the low-flow bathroom faucet were similar across treatments.

Ability. We investigate two possible ways in which households may have become better at using the technologies, and we do not find evidence for either one. First, water fixtures accumulate muck over time, especially in this region of Costa Rica, and households may have been motivated by the cash bonus to learn how to clean out the muck more efficiently. If it were the case that households got better at cleaning out muck, then we would expect to see fewer fixture removals in the bonus group for the stated reason that the fixture was “broken” or “clogged”. Table 5 shows that those reasons were given a bit less frequently in the bonus group, but not enough to rule out sampling variability as the source of the difference.

Second, some tasks require a fixed volume of water, like filling a one-gallon jug. Households may have been motivated by the cash bonus to find ways around the low-flow fixtures for those tasks, such as using an alternative spigot. If it were the case that households found ways around the low-flow fixtures for fixed-volume tasks, then we would expect to see fewer fixture removals in the bonus group for the stated reason that “low flow requires more time”. Table 5 shows that the frequency of that reason was similar in the bonus group and the no-bonus group.

6 Analytical results

Having demonstrated that increased exposure to a technology can reduce disadoption of the technology, we next develop intuition about the conditions under which a policymaker would find it optimal to offer a limited duration subsidy aimed at enhancing exposure to the technology. To develop the intuition, we build on the model introduced in Section 2.

Using the model, we contrast a limited duration subsidy with two more widely discussed subsidy options: a use subsidy offered in perpetuity conditional on use, and a purchase subsidy offered only at the time a good is initially acquired. Under conventional assumptions,

the use subsidy offered in perpetuity is optimal. In this section, we identify three features that are common to policy environments and that make a use subsidy offered in perpetuity suboptimal. We then show that both the use subsidy and the purchase subsidy may be outperformed by a limited duration subsidy, here called an exposure subsidy, when exposure-enhancing mechanisms are present in combination with those features.

The three features we consider that are common to policy environments and make a use subsidy suboptimal are: administrative costs, present bias, and liquidity constraints. These features make time-concentrated (i.e. frontloaded) subsidies more attractive than perpetual use subsidies because (a) present-biased and liquidity-constrained agents are more responsive to time-concentrated subsidies or (b) a social planner that faces subsidy administration costs can reduce these costs with time-concentrated subsidies. In contrast, the exposure-enhancing mechanisms tend to make time-dispersed subsidies more attractive than purchase subsidies because time-dispersed subsidies (a) give agents more opportunity to learn their match quality (information) and (b) give agents more opportunity to build up their stock of exposure (taste/ability).

Thus, when a social planner faces a combination of any of the three exposure-enhancing mechanisms and any of the three policy environment features, it can improve on a perpetual subsidy and a purchase subsidy by offering an exposure subsidy, defined as a subsidy that extends beyond the purchase point but ends after a limited duration. The combination is important. If the exposure-enhancing mechanisms are present, and the other features (administrative costs, present bias, and liquidity constraints) are absent, then a perpetual Pigouvian use subsidy is just as good as an exposure subsidy. On the other hand, if administrative costs, present bias, or liquidity constraints are present, and the exposure-enhancing mechanisms are absent, then the agent would either (a) use the good even without the subsidy, or (b) disadopt the good as soon as the subsidy is removed.⁶

⁶One exception to this is that a purchase subsidy could be adequate to induce persistent use in the

The ability and taste mechanisms are typically expressed the same way in formal models: using a good contributes to a stock of exposure, which subsequently raises marginal utility, raises marginal productivity, or reduces marginal cost. Even though these two mechanisms are typically expressed isomorphically, we mention them separately because they are conceptually distinct. Ability to use a good can change without taste for the good changing, and vice versa. The model introduced in Section 2 accomodates distinct dynamics for taste and ability, but the two mechanisms will be expressed isomorphically in the derivation of analytical results.

To show the conditions under which an exposure subsidy can be optimal, we focus here on a simple version of the model that includes administrative costs and the taste/ability mechanism but omits present bias, liquidity constraints, and the information mechanism. Appendix C shows that similar results hold when there is present bias or a liquidity constraint rather than administrative costs, and when the information mechanism is active rather than the taste/ability mechanism.

Agents. There is a population of homogeneous agents of measure one that make decisions in discrete time. In each period t , an agent chooses whether to use a good to maximize its discounted stream of expected utility:

$$U_t = \max_{r_t \in \{0,1\}} \sum_{j=0}^{\infty} \delta^j u_{t+j} \quad (3)$$

where $r \in \{0,1\}$ is a discrete choice variable to either use the good or not, and $\delta \in (0,1)$ is the agent's time discount factor.⁷

For simplicity we assume that the agent has a linear utility function in period t taking

presence of a liquidity constraint and a purchase price; in that case the absence of the purchase price in subsequent periods acts like an exposure-enhancing mechanism.

⁷The analytical results derived here are in the presence of administrative costs, which are formalized below when the social planner is introduced. Equation 3 can easily be adjusted to include present bias, as in Appendix Equation 19, or to include liquidity constraints, as in Appendix Equation 30.

the form:

$$u_t = u(r_t, S_t) = r_t \alpha_r + r_t S_t \alpha_{rS} + r_t \sigma_t - r_t p \mathbb{I}[\forall j < 0 : r_{t+j} = 0] \quad (4)$$

The term $S \geq 0$ is an exposure stock indicating taste or ability, and \mathbb{I} is an indicator function equal to one if the bracketed argument is true and zero if it is false. The term $\alpha_r < 0$ is the utility from immediate use of the good. The assumption of negative utility is needed to focus the model on encouraging exposure as a means to reduce disadoption. If $\alpha_r > 0$, then a purchase subsidy is always sufficient to encourage permanent use irrespective of exposure. The term α_{rS} is the utility derived from the gradual accumulation of exposure, and $\sigma_t \in [0, \sigma]$ is the subsidy set offered by the policymaker. The exposure stock evolves according to the law of motion in Equation 2, which we reproduce here:

$$S_{t+1} = (1 - d)(S_t + r_t)$$

where $d \in (0, 1)$ is a depreciation parameter.

If the agent does not use the good, then utility is zero. If the agent uses the good, then the agent derives utility from the net benefit of using the good (which could be negative) and from the subsidy. If the agent is using the good for the first time, then the agent also pays a price p .

Social planner. A social planner chooses a sequence of subsidies to maximize social welfare, which consists of the sum of the agent's utility and externalities net of subsidies and administrative costs. Each period the good is used, it generates a positive externality e . We assume that the sequence of subsidies is constrained to be some positive value σ for some number of periods k and, if k is finite, zero thereafter. In other words, the social planner can choose the subsidy level σ and duration k but cannot tailor the subsidy to be a different

magnitude in each individual period. In each period that the subsidy is nonzero, the social planner incurs an administrative cost a . We note that $k = 1$ corresponds to a purchase subsidy, $k = \infty$ corresponds to a perpetual use subsidy, and $1 < k < \infty$ corresponds to an exposure subsidy.⁸

The social planner chooses the subsidy level and duration to maximize welfare:

$$\max_{\sigma, k} \sum_{j=0}^{\infty} \delta^j (u_{t+j} + r_{t+j}e) - \sum_{j=0}^{k-1} \delta^j r_{t+j}(\sigma + a) \quad (5)$$

We assume that the social planner follows through on all promises made at the time the agent first uses the good, i.e. there are no obstacles to credibly committing to a subsidy level and duration.

Solution for the social planner. The social planner might choose to pay a subsidy σ to encourage the use of a good that generates a positive externality only if the price of the good is such that $p > p^*$, where p^* is defined as the highest price at which the agent would choose to use the good with zero subsidy:

$$p^* \equiv \left(\frac{1}{1-\delta}\right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d}\right) - \left(\frac{1}{1-\delta(1-d)}\right) \alpha_{rS} \left(\frac{1-d}{d}\right) \quad (6)$$

We now focus on the exposure stock S . S^* is the smallest exposure stock at which the agent would choose to continue using the good in perpetuity without a subsidy, after the price has been paid. In other words, once exposure has reached S^* the agent will choose not to disadopt the good, and the subsidy is not necessary. In the social planner's optimization,

⁸In our model we define the purchase subsidy as having a duration of $k=1$ periods. We can reasonably argue that this is a purchase subsidy given that time is discrete in our model, and using the good for one period is akin to bringing the good to the place where it will be used after being acquired.

S^* is defined as:

$$S^* \equiv -\left(\frac{1 - \delta(1 - d)}{1 - \delta}\right) \frac{\alpha_r}{\alpha_{rS}} - \left(\frac{\delta(1 - d)}{1 - \delta}\right) \quad (7)$$

The value of S^* and the speed at which exposure S accumulates will determine the duration of the subsidy. The threshold level of exposure (S^*) is decreasing in the return to exposure ($\frac{\partial S^*}{\partial \alpha_{rS}} < 0$), decreasing in the direct utility of the good ($\frac{\partial S^*}{\partial \alpha_r} < 0$), and increasing in the depreciation rate of exposure ($\frac{\partial S^*}{\partial d} > 0$). The sign of $\frac{\partial S^*}{\partial \delta}$ is ambiguous and depends on the relationship among the depreciation rate of exposure, the direct disutility, and the return to exposure. The sign of $\frac{\partial S^*}{\partial \delta}$ has the same sign as $d(1 - \frac{\alpha_r}{\alpha_{rS}}) - 1$. Appendix Section A gives more details on comparative statics around the threshold level of exposure.

Next we present three propositions that describe sufficient conditions under which a purchase subsidy, a perpetual use subsidy, or an exposure subsidy are optimal.

Proposition 1. *Conditions for the optimality of a purchase subsidy.* *Given $p > p^*$, a purchase subsidy ($k = 1$) with magnitude $\sigma = \sum_{j=0}^{\infty} \delta^j e - a$ is optimal if: (1) $\sum_{j=0}^{\infty} \delta^j e > a$ and (2) $0 \geq S^*$, where p^* and S^* are as defined above. Proof in appendix.*

In other words, a positive purchase subsidy is optimal if the present value of the positive externality exceeds the cost of administering the purchase subsidy (Condition (1)) and if either the accumulation of exposure reaches S^* instantaneously or exposure is not relevant to the decision (Condition (2), which, given that we defined $S \geq 0$ in equation (4), implies $S \geq 0 \geq S^*$).

Proposition 2. *Conditions for the optimality of a perpetual use subsidy.* *Given $p > p^*$, a perpetual use subsidy ($k = \infty$) of magnitude $\sigma = e - a$ is optimal if: (1) $e > a$ and (2) $\frac{1-d}{d} < S^*$, where p^* and S^* are as defined above. Proof in appendix.*

Condition (1) simply states that a perpetual use subsidy only makes sense if the value

of the externality is above the administrative costs of paying the subsidy in every period. Condition (2) implies that the threshold of exposure S^* is not reachable because it is above the maximum possible stock of exposure. Therefore, in the absence of the subsidy, the agent will never choose to use the good.

Proposition 3. *Conditions for the optimality of an exposure subsidy.* *Given $p > p^*$, an exposure subsidy of magnitude σ^* and duration k^* is optimal if: (1) $\sum_{j=0}^{\infty} \delta^j e > \sum_{j=0}^{k^*-1} \delta^j (\sigma^* + a)$ and (2) $0 < S^* < \frac{1-d}{d}$, where p^* and S^* are as defined above and k^* and σ^* are defined as follows:*

$$k^* \equiv \text{ceiling} \left(\frac{\log(\frac{1-d}{d} - S^*) - \log(\frac{1-d}{d} - S_t)}{\log(1-d)} \right)$$

$$\sigma^* \equiv \left(\frac{1-\delta}{1-\delta^{k^*}} \right) p - \left(\frac{1}{1-\delta^{k^*}} \right) \alpha_r - \left(\frac{1-d}{1-\delta^{k^*}} \right) \left(\frac{\delta}{1-\delta(1-d)} \right) \alpha_{rS}$$

Proof in appendix.

The first condition states that the present value of the externality exceeds the cost of administering the subsidy for k^* periods. The second condition guarantees that the stock of exposure S^* is attainable.

The subsidy stops at k^* , after which the social planner no longer incurs the administrative cost. The value of k^* is determined by the exposure threshold S^* and the parameter that determines the speed at which the stock of exposure increases (d). The intuition underlying the expression for σ^* is the following:

- The first term is positive and reflects a share of the price of the good to be paid in each period. Focusing on this term only, we can say that the shorter duration of subsidized exposure (i.e. the shorter k^*), the larger the share of the price that needs to be paid each period. The larger the price, the larger the needed subsidy.

- The second term is positive (because direct utility α_r is negative). The larger the utility (i.e. smaller the disutility) from using the good directly the smaller the subsidy. Moreover, the shorter k^* the smaller the optimal subsidy.
- Finally, the third term is negative and depends on the share of utility that comes from exposure. The higher α_{rS} , the smaller the needed subsidy. Once again, the shorter k^* , the smaller the optimal subsidy.

All else equal, if exposure plays a negligible role in the utility derived from the good, then a purchase subsidy will be optimal. On the other hand, if exposure accumulates slowly, then a perpetual use subsidy will be optimal as the utility from increased exposure will not be sufficient to ensure perpetual use. Importantly, if exposure accumulates in a middle range, then an exposure subsidy will be optimal. Those implications are reflected in the second condition of each proposition, which describes the range of values of S^* for which the exposure subsidy is optimal. Similarly, each proposition states the need to ensure that the present value of the externality is larger than the present value of the administrative costs, as otherwise society will be incurring a loss by paying the subsidy. Finally, the actual size of the exposure subsidy will depend on the duration of the subsidy, the disutility from using the good ($\frac{\partial u}{\partial \alpha_r} < 0$), and the indirect utility that comes from exposure ($\frac{\partial u}{\partial \alpha_{rS}} > 0$).

Appendix C presents versions of the model with (1) administrative costs and the information mechanism, (2) present bias and the taste/ability mechanism, (3) present bias and the information mechanism, (4) liquidity constraints and the taste/ability mechanism, and (5) liquidity constraints and the information mechanism. These derivations show that exposure subsidies can be optimal with any combination of one of the exposure-enhancing mechanisms—information, taste, and ability—and one of the time-concentrating features—administrative costs, present bias, and liquidity constraints. The intuition for the models with the taste/ability mechanism is similar to the version presented here: intermediate val-

ues of key parameters yield opportunities for an exposure subsidy to be optimal. Exposure subsidies are almost always optimal when the information mechanism is present—in that case the social planner should subsidize the good as long as the marginal social gain from doing so (i.e. helping incremental agents with high match quality learn that they have high match quality) exceeds the marginal social cost from doing so (i.e. “wasting” administrative resources on agents who already know their match quality).

Note that the cash bonus in the experiment was designed to generate exogenous variation in exposure, not to be an optimal exposure subsidy or even welfare-enhancing. Appendix Section D conducts a retrospective policy analysis and concludes that recruiting additional households (by offering a “purchase subsidy” in the form of free low-flow fixtures and free installation) would have been a better strategy in this context than subsidizing exposure at the specific level of the cash bonus offered in the experiment.

7 Conclusion

To encourage the adoption and persistence of technologies that yield external benefits, policy makers typically focus on one-time purchase (adoption) subsidies or perpetual use subsidies. As an alternative policy instrument, we introduce exposure subsidies, which are offered over a finite period and can increase the perceived net benefits from continued use of the technology. In a model that unifies the concepts and terminology from several literatures, we show that exposure subsidies can be preferred to one-time or perpetual subsidies under common field conditions, i.e. present bias, liquidity constraints, and administrative costs. Using a randomized field experiment, we empirically demonstrate that subsidy-induced exposure can indeed mitigate technology disadoption and we shed light on which exposure-enhancing mechanisms—information, taste, and ability—are operative in the study context.

Our results suggest that incentivizing exposure is a promising avenue for mitigating the

disadoption of policy-relevant behaviors. Nevertheless, our experiment only provides a proof of principle and our theoretical model only builds intuition about the optimal duration of subsidies. For field applications, more research in disparate contexts will be needed to characterize the prevalence and strength of exposure-enhancing mechanisms and the optimal subsidy magnitudes and durations. To help contribute to that goal, policymakers in the health, development, and environment fields can experiment with subsidy strategies that incentivize exposure rather than initial adoption or perpetual use.

Our experimental study adds low-flow water fixtures to the list of contexts in which exposure subsidies do generate persistent behavior change. Disadoption was also mitigated with short-term subsidies in the context of health care protocol adherence (Leonard and Masatu 2017), improved cookstoves (Usmani, Steele, and Jeuland 2017), and anti-malarial bednets (Dupas 2014).

Although we see disadoption of pro-social technologies in diverse contexts, overcoming disadoption seems to be especially relevant to technologies promoted in developing economies. In addition to the administrative costs and liquidity constraints that we model, state capacity constraints and political constraints frequently make use subsidies impossible to implement, and as a result technologies are not utilized optimally. Low-capacity states and NGOs may have an easier time implementing exposure subsidies precisely because they are short lived. Our analytical and theoretical results show that exposure subsidies may be able to achieve the same behavior change as use subsidies.

Data availability statement

The data and code underlying this research is available at https://osf.io/2cyaf/?view_only=0e1705f5a11f4c09bd9668b4170cb061.

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Appendix A Comparative statics with exposure threshold (for on-line publication)

This section elaborates on comparative statics around the threshold level of exposure S^* introduced in Section 6. Recall that:

$$S^* \equiv -\left(\frac{1 - \delta(1 - d)}{1 - \delta}\right) \frac{\alpha_r}{\alpha_{rS}} - \left(\frac{\delta(1 - d)}{1 - \delta}\right)$$

A larger return to exposure α_{rS} reduces the exposure threshold S^* :

$$\frac{\partial S^*}{\partial \alpha_{rS}} = \underbrace{\left(\frac{1 - \delta(1 - d)}{1 - \delta}\right)}_{(+)} \underbrace{\alpha_r}_{(-)} \underbrace{\alpha_{rS}^{-2}}_{(+)} < 0 \quad (8)$$

The smaller in magnitude the direct disutility α_r (i.e. as this negative parameter increases), the lower the exposure threshold S^* :

$$\frac{\partial S^*}{\partial \alpha_r} = -\left(\frac{1 - \delta(1 - d)}{1 - \delta}\right) \frac{1}{\alpha_{rS}} < 0 \quad (9)$$

The higher the depreciation of exposure stock d , the higher the exposure threshold:

$$\frac{\partial S^*}{\partial d} = \left(\frac{\delta}{1 - \delta}\right) \left(1 - \frac{\alpha_r}{\alpha_{rS}}\right) > 0 \quad (10)$$

The sign of $\frac{\partial S^*}{\partial \delta}$ depends on the relationship among the depreciation rate of exposure, the direct disutility, and the return to exposure. If $d(1 - \frac{\alpha_r}{\alpha_{rS}}) > 1$, then the derivative is positive:

$$\frac{\partial S^*}{\partial \delta} = \left(\frac{d(1 - \frac{\alpha_r}{\alpha_{rS}}) - 1}{(1 - \delta)^2}\right) \quad (11)$$

In other words, if direct disutility is large relative to the return to exposure, then the amount of required exposure is higher when the future is valued more highly. If direct disutility is low relative to the return to exposure, then the amount of required exposure is lower when the future is valued more highly.

Appendix B Proofs of propositions in the main text (for online publication)

We start with a lemma for a convenient expression of the exposure stock (through which the taste and ability mechanisms operate):

Lemma 1. Exposure stock. If the agent uses the good between period t and period $t + j$, then the exposure stock at time $t + j$ can be expressed as:

$$S_{t+j} = (1 - d)^j \left(S_t - \frac{1 - d}{d} \right) + \frac{1 - d}{d}$$

Proof.

$$\begin{aligned} S_{t+1} &= (1 - d)(S_t + 1) \\ S_{t+2} &= (1 - d)^2 S_t + (1 - d)^2 + (1 - d) \\ S_{t+j} &= (1 - d)^j S_t + \sum_{m=1}^j (1 - d)^m \\ S_{t+j} &= (1 - d)^j S_t + \frac{1 - (1 - d)^{j+1}}{1 - (1 - d)} (1 - d) \\ S_{t+j} &= (1 - d)^j \left(S_t - \frac{1 - d}{d} \right) + \frac{1 - d}{d} \quad \square \end{aligned}$$

Next, we derive the minimum number of periods of use required to attain a particular target exposure stock.

Lemma 2. Duration. If the exposure stock is S_t in period t , the agent is using the good in each period, and $\frac{1-d}{d} \geq \hat{S} \geq S_t$, then the minimum number of periods required to attain an exposure stock at least as large as \hat{S} is \hat{k} , where:

$$\hat{k} = \text{ceiling} \left(\frac{\log(\frac{1-d}{d} - \hat{S}) - \log(\frac{1-d}{d} - S_t)}{\log(1 - d)} \right)$$

Proof.

$$\begin{aligned}
S_{t+j} &= (1-d)^j \left(S_t - \frac{1-d}{d} \right) + \frac{1-d}{d} \\
\hat{S} &= (1-d)^{\tilde{k}} \left(S_t - \frac{1-d}{d} \right) + \frac{1-d}{d} \\
(1-d)^{\tilde{k}} \left(\frac{1-d}{d} - S_t \right) &= \frac{1-d}{d} - \hat{S} \\
\tilde{k} \log(1-d) + \log\left(\frac{1-d}{d} - S_t\right) &= \log\left(\frac{1-d}{d} - \hat{S}\right) \\
\tilde{k} &= \frac{\log\left(\frac{1-d}{d} - \hat{S}\right) - \log\left(\frac{1-d}{d} - S_t\right)}{\log(1-d)} \\
\hat{k} &= \text{ceiling}\left(\frac{\log\left(\frac{1-d}{d} - \hat{S}\right) - \log\left(\frac{1-d}{d} - S_t\right)}{\log(1-d)}\right)
\end{aligned}$$

The first line is from Lemma 1. The last step occurs because we must round up in discrete time. \square

Next, we show that, in the model presented in Section 6, subsidy policies that result in disadoption are not optimal.

Lemma 3. Disadoption. Policies that result in disadoption are not optimal.

Proof. Proof is by contradiction. Assume that (σ, k) is optimal and that it results in disadoption (so k is finite). If the policy is optimal, then $e > \sigma + a$. (If that were not true then a policy with subsidy equal to zero would be better.) Furthermore, extending the subsidy by one day would result in use for one more day with positive net welfare because period utility is increasing in the exposure stock and $e > \sigma + a$. So a policy of $(\sigma, k+1)$ is strictly better than (σ, k) . That contradicts the assumption that (σ, k) is optimal. \square

Lemma 4. Experience threshold. If the purchase price has already been paid and there is no subsidy, then the agent chooses to use the good in all subsequent periods if and

only if $S_t \geq S^*$, where:

$$S^* = -\left(\frac{1-\delta(1-d)}{1-\delta}\right)\frac{\alpha_r}{\alpha_{rS}} - \left(\frac{\delta(1-d)}{1-\delta}\right)$$

Proof. Following equations 3 and 4:

$$\begin{aligned} U(S_t) &= \max_{r_t} \sum_{j=0}^{\infty} \delta^j \left(\alpha_r r_{t+j} + \alpha_{rS} r_{t+j} S_{t+j} + \sigma_{t+j} r_{t+j} \right) \\ &= \max_{r_t} \sum_{j=0}^{\infty} \delta^j \left(\alpha_r r_{t+j} + \alpha_{rS} r_{t+j} \left((1-d)^j \left(S_t - \frac{1-d}{d} \right) + \frac{1-d}{d} \right) \right) \\ &= \max_{r_t} \sum_{j=0}^{\infty} \delta^j r_{t+j} \left(\alpha_r + \alpha_{rS} \left((1-d)^j \left(S_t - \frac{1-d}{d} \right) + \frac{1-d}{d} \right) \right) \\ &= \max \left\{ \left(\frac{1}{1-\delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} \right) + \left(\frac{1}{1-\delta(1-d)} \right) \alpha_{rS} \left(S_t - \frac{1-d}{d} \right), 0 \right\} \end{aligned}$$

The substitution for S_{t+j} follows from lemma 1. The subsidy substitution follows from the assumption that there is no subsidy. Using the good in one period implies the exposure stock will be larger in the next period, $r_t = 1 \implies S_{t+1} \geq S_t$. The period utility function is increasing in the exposure stock, so if the good is used in one period then it will also be used in the next period. To find the exposure threshold, we set the utility of using the good equal to the utility of not using the good.

$$\begin{aligned} 0 &= \left(\frac{1}{1-\delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} \right) + \left(\frac{1}{1-\delta(1-d)} \right) \alpha_{rS} \left(S^* - \frac{1-d}{d} \right) \\ S^* - \frac{1-d}{d} &= - \left(\frac{1-\delta(1-d)}{1-\delta} \right) \left(\frac{\alpha_r}{\alpha_{rS}} + \frac{1-d}{d} \right) \\ S^* &= - \left(\frac{1-\delta(1-d)}{1-\delta} \right) \frac{\alpha_r}{\alpha_{rS}} - \frac{1-d}{d} \left(\frac{1-\delta+\delta d}{1-\delta} - \frac{1-\delta}{1-\delta} \right) \\ S^* &= - \left(\frac{1-\delta(1-d)}{1-\delta} \right) \frac{\alpha_r}{\alpha_{rS}} - \left(\frac{\delta(1-d)}{1-\delta} \right) \quad \square \end{aligned}$$

Building on these lemmas, we prove Proposition 1:

Proposition 1. Purchase subsidy. A purchase subsidy with $\sigma = \sum_{j=0}^{\infty} \delta^j e - a$ and $k = 1$ is optimal if: (1) $p > p^*$, (2) $0 \geq S^*$, and (3) $\sum_{j=0}^{\infty} \delta^j e > a$, where p^* and S^* are defined as follows:

$$p^* \equiv \left(\frac{1}{1-\delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} \right) - \left(\frac{1}{1-\delta(1-d)} \right) \alpha_{rS} \left(\frac{1-d}{d} \right)$$

$$S^* \equiv - \left(\frac{1-\delta(1-d)}{1-\delta} \right) \frac{\alpha_r}{\alpha_{rS}} - \left(\frac{\delta(1-d)}{1-\delta} \right)$$

Proof. Using the good in one period implies the exposure stock will be larger in the next period, $r_t = 1 \implies S_{t+1} \geq S_t$. The period utility function is increasing in the exposure stock, so if the good is used in one period then an agent would only choose to disadopt (use the good in period t but not in period $t+1$) if the subsidy is removed. Following equations 3 and 4:

$$\begin{aligned}
U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} -r_t p + \sum_{j=0}^{\infty} \delta^j (r_{t+j} \alpha_r + r_{t+j} S_{t+j} \alpha_{rS}) + \sum_{j=0}^{k-1} \delta^j r_{t+j} \sigma \\
&= \max \left\{ \underbrace{-p + \left(\frac{1-\delta^k}{1-\delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} + \sigma \right) - \left(\frac{1-\delta^k(1-d)^k}{1-\delta(1-d)} \right) \alpha_{rS} \left(\frac{1-d}{d} \right)}_{r_{t+j}=1 \text{ for } j < k \text{ and } r_{t+j}=0 \text{ for } j \geq k}, \right. \\
&\quad \underbrace{-p + \left(\frac{1}{1-\delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} \right) - \left(\frac{1}{1-\delta(1-d)} \right) \alpha_{rS} \left(\frac{1-d}{d} \right) + \left(\frac{1-\delta^k}{1-\delta} \right) \sigma}_{r_{t+j}=1 \text{ for } j \geq 0} \\
&\quad \left. \underbrace{0}_{r_{t+j}=0 \text{ for } j \geq 0} \right\}
\end{aligned}$$

There are three possibilities: (1) the agent may use the good forever (perpetual use), (2) the agent may use the good until the subsidy is removed (disadoption), or (3) the agent may decline to use the good (non-adoption). By Lemma 3, the optimal policy will result in either perpetual use or non-adoption. In order to prove that $\sigma = \sum_{j=0}^{\infty} \delta^j e - a$ and $k = 1$ is optimal, we will show that (a) the subsidy achieves perpetual use if and only if perpetual

use is socially optimal, and (b) perpetual use cannot be achieved at lower cost.

First, we show that if the subsidy achieves perpetual use, then it is socially optimal. Then from the agent's problem we know that:

$$0 < -p + \left(\frac{1}{1-\delta}\right)\left(\alpha_r + \alpha_{rs}\frac{1-d}{d}\right) - \left(\frac{1}{1-\delta(1-d)}\right)\alpha_{rs}\left(\frac{1-d}{d}\right) + \sum_{j=0}^{\infty} \delta^j e - a$$

This is exactly the condition that implies that perpetual use is socially optimal.

Next, we show that if perpetual use is socially optimal, then the subsidy achieves perpetual use. By assumption, $0 \geq S^*$. That means that if the purchase price were paid (i.e. the agent used the good for at least one period), then the choice problem would be equivalent to the conditions in Lemma 4, and the subsidy achieves perpetual use. Furthermore, the condition from the agent's problem above, which is an implication of perpetual use being socially optimal, shows that the agent would also use the good in the first period. So we have shown that the subsidy achieves perpetual use if and only if perpetual use is socially optimal.

To show perpetual use cannot be achieved at lower cost, we note that, by assumption, $p > p^*$. Applying that condition to the agent's problem, we see that the agent is not willing to purchase the good without a subsidy, so perpetual use cannot be achieved in fewer periods than $k = 1$. From the perspective of a social planner, one period of subsidy minimizes administrative costs. To the extent that the subsidy magnitude $\sigma = \sum_{j=0}^{\infty} \delta^j e - a$ exceeds the minimum required for perpetual use, it is a transfer to the agent, not a social loss. So we have shown (b). \square

Next we prove Proposition 2:

Proposition 2. Use subsidy. A use subsidy with $\sigma = e - a$ and $k = \infty$ is optimal if: (1) $p > p^*$, (2) $\frac{1-d}{d} < S^*$, and (3) $e > a$, where p^* and S^* are as defined in Proposition 1.

Proof. By assumption, $p > p^*$. Applying that condition to the agent's problem, we

see that the agent is not willing to purchase the good without a subsidy. By assumption, $\frac{1-d}{d} < S^*$. The largest possible value for the exposure stock is $\frac{1-d}{d}$, so this assumption implies that perpetual use cannot be achieved with a subsidy of finite duration. By assumption, $e > a$. A subsidy of $\sigma = e - a$ is a Pigouvian perpetual use subsidy adjusted for administrative costs. If it induces use initially, then it will induce perpetual use. If it induces perpetual use then the net private cost is at least zero, and the externalities net of administrative costs have been internalized by the agent by setting the subsidy to exactly $\sigma = e - a$. This subsidy is no worse than a zero subsidy (if it results in non-adoption), better than any subsidy of finite duration (by Lemma 3), and possibly better than a zero subsidy (if it results in perpetual use). It is in the set of best possible policies, but possibly not unique (if it results in non-adoption). \square

Next we prove Proposition 3:

Proposition 3. Exposure subsidy. An exposure subsidy with $\sigma = \sigma^*$ and $k = k^*$ is optimal if: (1) $p > p^*$, (2) $0 < S^* < \frac{1-d}{d}$, and (3) $\sum_{j=0}^{\infty} \delta^j e > \sum_{j=0}^{k^*-1} \delta^j (\sigma^* + a)$, where p^* and S^* are as defined in Proposition 1 and k^* and σ^* are defined as follows:

$$k^* \equiv \text{ceiling} \left(\frac{\log(\frac{1-d}{d} - S^*) - \log(\frac{1-d}{d} - S_t)}{\log(1-d)} \right)$$

$$\sigma^* \equiv \left(\frac{1-\delta}{1-\delta^{k^*}} \right) p - \left(\frac{1}{1-\delta^{k^*}} \right) \alpha_r - \left(\frac{1-d}{1-\delta^{k^*}} \right) \left(\frac{\delta}{1-\delta(1-d)} \right) \alpha_{rS}$$

Proof. In order to prove that $\sigma = \sigma^*$ and $k = k^*$ is optimal, we will show that (a) it achieves perpetual use, (b) perpetual use cannot be achieved at lower cost, and (c) perpetual use is better than non-adoption.

By assumption, $0 < S^* < \frac{1-d}{d}$. That means there is some exposure stock greater than zero that is attainable in a finite number of periods at which the agent would choose to continue using the good without a subsidy.

By assumption, $p > p^*$. Applying that condition to the agent's problem, we see that the agent is not willing to purchase the good without a subsidy. By Lemma 2, k^* is the minimum number of periods required to attain an exposure stock of at least S^* . So among all possible nonzero subsidy policies, perpetual use cannot be achieved at lower administrative cost.

We consider whether an exposure subsidy with $\sigma = \sigma^*$ and $k = k^*$ achieves perpetual use. Using the agent's indifference condition between perpetual use and nonadoption (written out in the proof for Proposition 1), we see that σ^* is the minimum subsidy required to achieve perpetual use when $k = k^*$. Thus, this policy achieves perpetual use.

Because σ^* is chosen such that the discounted stream of utility is exactly zero, the externality generated by perpetual use must exceed both the administrative cost of the subsidy (a) and the direct cost of the subsidy (σ^*), which is true by assumption: $\sum_{j=0}^{\infty} \delta^j e > \sum_{j=0}^{k^*-1} \delta^j (\sigma^* + a)$. \square

Appendix C Additional analytical results (for online publication)

We consider versions of the model with each possible combination of time-concentrating feature (administrative costs, present bias, or liquidity constraints) and an exposure-enhancing mechanism (information or taste/ability). The main text presents analytical results for the model with administrative costs and the taste/ability mechanism. The other five combinations are presented in this appendix.

We present the models with one time-concentrating feature and one exposure-enhancing mechanism at a time for simplicity. There is no reason to think there would be a negative interaction among the time-concentrating features or exposure-enhancing mechanisms if they were present simultaneously. In other words, if an exposure subsidy can be optimal in these simple versions of the model, then an exposure subsidy can also be optimal with multiple time-concentrating features or exposure-enhancing mechanisms.

C.1 Model with administrative costs and information mechanism

Intuition. With administrative costs and the information mechanism, the social planner chooses the subsidy duration k such that the net marginal welfare impact of subsidizing the good for one additional period would be approximately zero. The positive component of the welfare impact of subsidizing the good for one additional period is that more agents with high match quality learn that they have high match quality, and therefore they continue using the good and continue generating the positive externality after the subsidy is no longer offered. The negative component of the welfare impact includes both (i) the administrative cost and (ii) the social cost of subsidizing agents with low match quality. The social planner chooses the subsidy level σ that minimally induces an agent with unknown match quality to try the good.

One additional period of subsidy has a diminishing benefit (because there are fewer

uninformed agents with high match quality remaining) and a constant or diminishing cost (depending on whether agents with low match quality continue using the subsidized good after they learn that they have low match quality). A perpetual use subsidy with the same present value as an exposure subsidy chosen this way would incur larger administrative costs and subsidize more agents with low match quality. A purchase subsidy with the same present value would induce fewer agents with high match quality to learn their types and would miss out on the positive externality that those agents would have generated.

Agents. There is a population of agents of measure one. Each agent chooses in each period whether or not to use a good to maximize the discounted stream of expected utility. If the agent does not use the good, then utility is zero. If the agent uses the good, then the agent derives utility from the direct net benefit of using the good (which could be negative) and from a subsidy σ set by a policymaker. If the agent is using the good for the first time, then the agent also pays a price p . The discounted stream of expected utility in period t is:

$$U_t = \max_{r_t \in \{0,1\}} \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} u_{t+j} dF_t(\theta) \quad (12)$$

where $r \in \{0, 1\}$ is a discrete choice to either use the good or not and $\delta \in (0, 1)$ is the agent's time discount factor.

Utility in period t takes the form:

$$u_t = u(r_t, \theta_i) = r_t \alpha_r + r_t \theta_i \alpha_{r\theta} + r_t \sigma_t - r_t p \mathbb{I}[\forall j < 0 : r_{t+j} = 0] \quad (13)$$

where θ is match quality and \mathbb{I} is an indicator function equal to one if the argument is true and zero if it is false. The population comprises agents with low and high match quality between the agent and the good. We assume that a fraction q of agents have low match quality, and $1 - q$ have high match quality, such that the population distribution of match

quality can be expressed with the following probability mass function f with $q \in (0, 1)$:

$$f(\theta) = \begin{cases} q & \text{if } \theta = 0 \\ 1 - q & \text{if } \theta = 1 \end{cases} \quad (14)$$

We assume the signal is either fully informative or totally uninformative, such that the distribution of signals can be expressed with the following probability mass function g with $\gamma \in (0, 1)$:

$$g(\omega_t | \theta_i) = \begin{cases} \gamma & \text{if } \omega_t = -1 \\ 1 - \gamma & \text{if } \omega_t = \theta_i \end{cases} \quad (15)$$

Social planner. A social planner chooses a sequence of subsidies to maximize social welfare, which consists of the sum of all agents' utility and externalities net of subsidies and administrative costs. Each period the good is used, it generates a positive externality e . We assume the sequence of subsidies is constrained to be some positive value σ for some number of periods k and, if k is finite, zero thereafter. In other words, the social planner can choose the subsidy level σ and duration k but cannot tailor the subsidy to be a different magnitude in each individual period. In each period that the subsidy is nonzero, the social planner incurs an administrative cost a . The social planner thus chooses the subsidy level and duration to maximize welfare:

$$\max_{\sigma, k} \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (u_{t+j} + r_{t+j}e) dF_t(\theta) - \sum_{j=0}^{k-1} \delta^j r_{t+j}(\sigma + a) \quad (16)$$

where F is the cumulative distribution function corresponding to f .

We assume that the social planner follows through on all promises made at the time the agent first uses the good, i.e. there are no obstacles to credibly committing to a subsidy

level and duration.

We assume:

- The net private benefit to an agent who knows she has high match quality is positive:

$$\alpha_r + \alpha_{r\theta} > 0$$

- The net social benefit for an agent with low match quality is negative: $\alpha_r + e < 0$

- The net private benefit to an agent who does not know her match quality is negative:⁹

$$\alpha_r + \alpha_{r\theta}(1 - q) + (1 - q)(1 - \gamma)\frac{\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta}) < 0$$

- The net social benefit for an agent who does not know her match quality is positive:

$$\alpha_r + \alpha_{r\theta}(1 - q) + e + (1 - q)(1 - \gamma)\frac{\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta} + e) > 0$$

Solution for the agents. If $k = 1$ and $p = 0$, then expected utility at time t is:

$$\begin{aligned} U_t(\sigma, k) &= \max_{r_t \in \{0, 1\}} r_t \sigma + \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) \\ &= \max \left\{ \alpha_r + \alpha_{r\theta}(1 - q) + \sigma + (1 - q)(1 - \gamma)\frac{\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta}), 0 \right\} \end{aligned}$$

Pooling equilibrium. Define $\hat{\sigma}$ as the minimum subsidy such that an agent who knows she has low match quality chooses to use the good when $k = 1$ and $p = 0$: $\hat{\sigma} = -\alpha_r$. If the agent has not previously used the good (i.e. the price p must be paid) and $\sigma \geq \hat{\sigma}$ (i.e. an agent who knows she has low match quality behaves the same way as an agent with unknown

⁹If this assumption does not hold, then the agent would try the good on her own, and a subsidy would not be necessary.

match quality), then expected utility at time t is:

$$\begin{aligned}
U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} -r_t p + \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) + \sum_{j=0}^{k-1} \delta^j r_{t+j} \sigma \\
&= \max \left\{ 0, \quad -p + \frac{1 - \delta^k}{1 - \delta} \left(\alpha_r + (1 - q) \alpha_{r\theta} + \sigma \right) \right. \\
&\quad \left. + (1 - q)(1 - \gamma^k) \frac{\delta^k}{1 - \delta} \left(\alpha_r + \alpha_{r\theta} \right) \right\}
\end{aligned}$$

Separating equilibrium. Define $\tilde{\sigma}$ as the minimum subsidy such that an uninformed agent chooses to use the good when $k = 1$ and $p = 0$:

$$\tilde{\sigma} = -\alpha_r - \alpha_{r\theta}(1 - q) - (1 - q)(1 - \gamma) \frac{\delta}{1 - \delta} (\alpha_r + \alpha_{r\theta})$$

If the agent has not previously used the good (i.e. the price p must be paid) and $\tilde{\sigma} < \sigma < \hat{\sigma}$ (i.e. an agent who knows she has low match quality behaves differently from an agent with unknown match quality), then expected utility at time t is:

$$\begin{aligned}
U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} -r_t p + \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) + \sum_{j=0}^{k-1} \delta^j r_{t+j} \sigma \\
&= \max \left\{ 0, \quad -p + \underbrace{(1 - q) \frac{1 - \delta^k}{1 - \delta} \left(\alpha_r + \alpha_{r\theta} + \sigma \right)}_{\text{utility of high match quality during first } k \text{ periods}} \right. \\
&\quad + \underbrace{(q) \frac{1 - \delta^k \gamma^k}{1 - \delta \gamma} \left(\alpha_r + \sigma \right)}_{\text{utility of low match quality during first } k \text{ periods}} \\
&\quad \left. + \underbrace{(1 - q)(1 - \gamma^k) \frac{\delta^k}{1 - \delta} \left(\alpha_r + \alpha_{r\theta} \right)}_{\text{utility of known high match quality from period } k \text{ onward}} \right\}
\end{aligned}$$

There are three possibilities: (1) the agent learns she has high match quality, (2) the agent learns she has low match quality, (3) the agent does not learn her match quality. If she learns she has low match quality, then she immediately disadopts the good. If she does

not learn her match quality, then she disadopts when the subsidy ends after k periods. If she learns she has high match quality, then she continues using the good in perpetuity even after the subsidy ends.

Solution for the social planner. There are two policy regimes in which a subsidy induces use by some agents:

- Pooling equilibrium. All agents use the good as long as the subsidy is offered. After the subsidy ends, only agents who have discovered that they have high match quality use the good.
- Separating equilibrium. Agents with unknown match quality and agents who know they have high match quality use the good as long as the subsidy is offered. After the subsidy ends, only agents who have discovered that they have high match quality use the good.

We derive the optimal subsidy size and duration in each equilibrium, then we derive a condition that describes whether the separating equilibrium is supportable. If the separating equilibrium is supportable, then the social planner chooses the optimal subsidy size and duration from the separating equilibrium. If the separating equilibrium is not supportable, then the social planner chooses the optimal subsidy size and duration from the pooling equilibrium.

Pooling equilibrium. When the social planner subsidizes the good, the goal is to induce agents who do not know their match quality to use the good and possibly learn their match quality. The marginal social net benefit of one period of subsidy is (1) the net social benefit of unknown match quality agents using the good, plus (2) the net social benefit of low match quality agents using the good, plus (3) the fraction of agents who learn that they have high match quality times the social benefit of their future choices to use the good, minus (4) the administrative cost of the subsidy. We find the number of periods k that the subsidy is

offered by setting the marginal social net benefit equal to zero.

$$\begin{aligned}
0 = & \gamma^{\tilde{k}} [\alpha_r + \alpha_{r\theta}(1 - q) + e] \\
& + (1 - \gamma^{\tilde{k}})(q) [\alpha_r + e] \\
& + \gamma^{\tilde{k}}(1 - \gamma)(1 - q) \left[\frac{\delta}{1 - \delta} (\alpha_r + \alpha_{r\theta} + e) \right] \\
& - [a]
\end{aligned}$$

We solve for \tilde{k} and round up to find the optimal subsidy duration k^* :

$$k_{\text{pool}}^* = \text{ceiling} \left(\frac{\log(a - q(\alpha_r + e)) - \log\left(\frac{1 - \delta\gamma}{1 - \delta}(1 - q)(\alpha_r + \alpha_{r\theta} + e)\right)}{\log(\gamma)} \right)$$

Next, using the indifference condition from the pooling equilibrium solution for the agents, we find the subsidy level σ^* that makes an agent with unknown match quality indifferent between using the good and not using the good for the first time:

$$\sigma_{\text{pool}}^* = \left(\frac{1 - \delta}{1 - \delta^{k^*}} \right) p - \alpha_r - (1 - q)\alpha_{r\theta} - (1 - q)(1 - \gamma^{k^*}) \left(\frac{\delta^{k^*}}{1 - \delta^{k^*}} \right) (\alpha_r + \alpha_{r\theta})$$

Separating equilibrium. When the social planner subsidizes the good, the goal is to induce agents who do not know their match quality to use the good and possibly learn their match quality. The marginal social net benefit of one period of subsidy is (1) the net social benefit of unknown match quality agents using the good, plus (2) the fraction of agents who learn that they are high match quality times the social benefit of their future choices to use the good, minus (3) the fraction of agents who already knew they were high match quality times the administrative cost of the subsidy. We find the number of periods k that the subsidy is

offered by setting the marginal benefit equal to zero.

$$\begin{aligned}
0 &= \gamma^{\tilde{k}} [\alpha_r + \alpha_{r\theta}(1 - q) + e - a] \\
&\quad + \gamma^{\tilde{k}}(1 - \gamma)(1 - q) \left[\frac{\delta}{1 - \delta} (\alpha_r + \alpha_{r\theta} + e) \right] \\
&\quad - (1 - \gamma^{\tilde{k}})(1 - q) [a]
\end{aligned}$$

We solve for \tilde{k} and round up to find the optimal subsidy duration k^* :

$$k_{\text{sep}}^* = \text{ceiling} \left(\frac{\log(a - qa) - \log \left(\alpha_r + \alpha_{r\theta}(1 - q) + e + \frac{\delta(1-\gamma)(1-q)}{1-\delta} (\alpha_r + \alpha_{r\theta} + e) - qa \right)}{\log(\gamma)} \right)$$

Next, using the indifference condition from the separating equilibrium solution for the agents, we find the subsidy level that makes an agent with unknown match quality indifferent between using the good and not using the good for the first time:

$$\begin{aligned}
\sigma_{\text{sep}}^* &= -\alpha_r + \left[(1 - q) \frac{1 - \delta^{k^*}}{1 - \delta} + (q) \frac{1 - \delta^{k^*} \gamma^{k^*}}{1 - \delta \gamma} \right]^{-1} \left[p - \left((1 - q) \frac{1 - \delta^{k^*}}{1 - \delta} \right) (\alpha_{r\theta}) \right. \\
&\quad \left. - \left((1 - q)(1 - \gamma^{k^*}) \frac{\delta^{k^*}}{1 - \delta} \right) (\alpha_r + \alpha_{r\theta}) \right]
\end{aligned}$$

Recall that, for $k = 1$ and $p = 0$, the minimum subsidy to induce a known low match quality to use the good is $\hat{\sigma} = -\alpha_r$ and the minimum subsidy to induce an uninformed agent to use the good:

$$\tilde{\sigma} = -\alpha_r - \alpha_{r\theta}(1 - q) - (1 - q)(1 - \gamma) \frac{\delta}{1 - \delta} (\alpha_r + \alpha_{r\theta})$$

If $k^* = 1$ and $p = 0$, then $\sigma^* = \tilde{\sigma}$ and a separating equilibrium is supportable. The

optimal subsidy in the separating equilibrium σ^* is increasing in k^* and p . The separating equilibrium is supportable for $\tilde{\sigma} < \sigma^* < \hat{\sigma}$. If $\sigma^* \geq \hat{\sigma}$ then the optimal subsidy size and duration is set according to the pooling equilibrium.

The optimal subsidy duration k^* is a decreasing function of administrative cost a . Using the formula from the pooled equilibrium:

$$\frac{\partial k^*}{\partial a} = \underbrace{\frac{1}{a - q(\alpha_r + e)}}_{(+)} \underbrace{\frac{1}{\log(\gamma)}}_{(-)} < 0 \quad (17)$$

The first expression is positive because $\alpha_r + e < 0$, and the second expression is negative because $\gamma < 1$.

The optimal subsidy duration k^* is an increasing function of the magnitude of match quality difference $\alpha_{r\theta}$. Using the formula from the pooled equilibrium:

$$\frac{\partial k^*}{\partial \alpha_{r\theta}} = \underbrace{\frac{1}{\alpha_r + \alpha_{r\theta} + e}}_{(+)} \underbrace{\frac{1}{\log(\gamma)}}_{(-)} \underbrace{(-1)}_{(-)} > 0 \quad (18)$$

The first expression is positive because $\alpha_r + \alpha_{r\theta} > 0$, and the second expression is negative because $\gamma < 1$.

C.2 Model with present bias and taste/ability mechanism

Intuition. With present bias and the taste/ability mechanism, the social planner chooses the minimal exposure subsidy duration k such that the agent, having built up a sufficient exposure stock, would continue using the good on her own after the subsidy is removed. The social planner chooses the exposure subsidy level σ such that the present value of the subsidy matches the present value of the externalities in perpetuity. An exposure subsidy chosen this way can be better than a perpetual use subsidy if the portion of the perpetual use subsidy

delivered after the first period is so heavily discounted by a present-biased agent that it results in nonadoption. An exposure subsidy can be better than a purchase subsidy because under the purchase subsidy the agent would never attain sufficient exposure to continue using the good on her own, thus resulting in adoption in the first period and subsequent disadoption.

Agents. There is a population of identical agents of measure one. Each agent chooses in each period whether or not to use a good to maximize the discounted stream of expected utility. If the agent does not use the good, then utility is zero. If the agent uses the good, then the agent derives utility from the direct net benefit of using the good (which could be negative) and from a subsidy σ set by a policymaker. If the agent is using the good for the first time, then the agent also pays a price p . The agent is present-biased in the sense that the discount applied between the current period and the next period is larger than the discount applied between any other two consecutive periods (quasi-hyperbolic discounting or beta-delta discounting). The discounted stream of utility in period t is:

$$U_t = \max_{r_t \in \{0,1\}} u_t + \beta \sum_{j=1}^{\infty} \delta^j u_{t+j} \quad (19)$$

where $r \in \{0,1\}$ is a discrete choice to either use the good or not, $\delta \in (0,1)$ is the agent's time discount factor, and $\beta \in [0,1]$ expresses the extent of the agent's present bias (smaller β implies greater present bias).

Utility in period t takes the form:

$$u_t = u(r_t, S_t) = r_t \alpha_r + r_t S_t \alpha_{rS} + r_t \sigma_t - r_t p \mathbb{I}[\forall j < 0 : r_{t+j} = 0] \quad (20)$$

where $S \geq 0$ is an exposure stock indicating taste or ability and \mathbb{I} is an indicator function equal to one if the argument is true and zero if it is false. The exposure stock evolves

according to the following law of motion:

$$S_{t+1} = (1 - d)(S_t + r_t) \quad (21)$$

where $d \in (0, 1)$ is a depreciation parameter.

Social planner. A social planner chooses a sequence of subsidies to maximize social welfare, which consists of the sum of the agent's utility and externalities net of subsidies. Unlike the agent, the social planner uses a consistent discount rate of δ , i.e. even though the agent is present-biased the social planner is not. Each period the good is used, it generates a positive externality e . We assume the sequence of subsidies is constrained to be some positive value σ for some number of periods k and, if k is finite, zero thereafter. In other words, the social planner can choose the subsidy level σ and duration k but cannot tailor the subsidy to be a different magnitude in each individual period. The social planner thus chooses the subsidy level and duration to maximize welfare:

$$\max_{\sigma, k} \sum_{j=0}^{\infty} \delta^j (u_{t+j} + r_{t+j}e) - \sum_{j=0}^{k-1} \delta^j r_{t+j}(\sigma) \quad (22)$$

We assume that the social planner follows through on all promises made at the time the agent first uses the good, i.e. there are no obstacles to credibly committing to a subsidy level and duration.

Solution for the agents. If the agent has not previously used the good (i.e. $S_t = 0$

and the price p must be paid), then expected utility at time t is:

$$\begin{aligned}
U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} r_t \left(\alpha_r + S_t \alpha_{rS} + \sigma - p \right) + \beta \sum_{j=1}^{\infty} \delta^j (r_{t+j} \alpha_r + r_{t+j} S_{t+j} \alpha_{rS}) + \beta \sum_{j=1}^{k-1} \delta^j r_{t+j} \sigma \\
&= \max \left\{ \left(\alpha_r + S_t \alpha_{rS} + \sigma - p \right) + \beta \left(\frac{\delta - \delta^k}{1 - \delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} + \sigma \right) \right. \\
&\quad \underbrace{- \beta \left(\frac{\delta(1-d) - \delta^k(1-d)^k}{1 - \delta(1-d)} \right) \alpha_{rS} \left(\frac{1-d}{d} \right)}_{r_{t+j}=1 \text{ for } j < k \text{ and } r_{t+j}=0 \text{ for } j \geq k}, \\
&\quad \left(\alpha_r + S_t \alpha_{rS} + \sigma - p \right) + \beta \left(\frac{\delta}{1 - \delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} \right) \\
&\quad \underbrace{- \beta \left(\frac{\delta(1-d)}{1 - \delta(1-d)} \right) \alpha_{rS} \left(\frac{1-d}{d} \right) + \beta \left(\frac{\delta - \delta^k}{1 - \delta} \right) \sigma}_{r_{t+j}=1 \text{ for } j \geq 0}, \\
&\quad \left. \underbrace{0}_{r_{t+j}=0 \text{ for } j \geq 0} \right\}
\end{aligned}$$

There are three possibilities: (1) the agent may use the good forever (perpetual use), (2) the agent may use the good until the subsidy is removed (disadoption), or (3) the agent may decline to use the good (non-adoption).

Solution for the social planner. A policy that results in disadoption cannot be optimal. Proof is by contradiction. Suppose that (σ, k) were optimal and that it resulted in disadoption (so k is finite). If the policy is optimal, then $e > \sigma$. (If that were not true then a policy with subsidy equal to zero would be better.) Furthermore, extending the subsidy by one day would result in use for one more day with positive net welfare because period utility is increasing in the exposure stock and $e > \sigma$. So a policy of $(\sigma, k+1)$ is strictly better than (σ, k) . That contradicts the assumption that (σ, k) is optimal.

So the optimal policy either results in perpetual use or non-adoption.

First, we find the exposure threshold at which an agent would continue using the good

if the good had already been used in prior periods:

$$S^* = -\left(\frac{1 - \delta(1 - d)}{1 - \delta}\right) \frac{\alpha_r}{\alpha_{rS}} - \left(\frac{\delta(1 - d)}{1 - \delta}\right)$$

Use subsidy. If $S^* \geq \frac{1-d}{d}$, then perpetual use can only be achieved with an ongoing use subsidy with $k = \infty$ and $\sigma = e$ is optimal.

The agent uses the good in perpetuity if:

$$\left(\alpha_r + S_t \alpha_{rS} + e - p\right) + \beta \left(\frac{\delta}{1 - \delta}\right) \left(\alpha_r + \alpha_{rS} \frac{1 - d}{d}\right) - \beta \left(\frac{\delta(1 - d)}{1 - \delta(1 - d)}\right) \alpha_{rS} \left(\frac{1 - d}{d}\right) + \beta \left(\frac{\delta}{1 - \delta}\right) e > 0$$

Exposure subsidy. If $S^* > 0$ and $S^* < \frac{1-d}{d}$, then perpetual use can be achieved with a subsidy of finite duration. The minimum number of periods required for the agent to reach the exposure threshold (and continue using the good without a subsidy) is:

$$k^* = \text{ceiling} \left(\frac{\log(\frac{1-d}{d} - S^*) - \log(\frac{1-d}{d} - S_t)}{\log(1 - d)} \right)$$

We consider the following exposure subsidy, which has the same discounted value as the externalities in perpetuity:

$$\sigma^* = \frac{1}{1 - \delta^{k^*}} e$$

This exposure subsidy has the effect of concentrating the subsidies in a shorter time interval. Because the agent is present-biased, subsidies in the first period have a larger impact on the present value of discounted utility than subsidies in later periods with the same present value from the social planner's perspective.

The agent uses the good in perpetuity if:

$$\begin{aligned} & \left(\alpha_r + S_t \alpha_{rS} + \frac{1}{1 - \delta^{k^*}} e - p \right) + \beta \left(\frac{\delta}{1 - \delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1 - d}{d} \right) \\ & - \beta \left(\frac{\delta(1 - d)}{1 - \delta(1 - d)} \right) \alpha_{rS} \left(\frac{1 - d}{d} \right) + \beta \left(\frac{\delta - \delta^k}{1 - \delta} \right) \frac{1}{1 - \delta^{k^*}} e > 0 \end{aligned}$$

Thus, the exposure subsidy ($\sigma^* = \frac{1}{1 - \delta^{k^*}} e$) is superior to a use subsidy ($\sigma = e$) if:

$$\frac{1}{1 - \delta^{k^*}} + \beta \left(\frac{\delta - \delta^{k^*}}{1 - \delta} \right) \frac{1}{1 - \delta^{k^*}} > \eta > 1 + \beta \left(\frac{\delta}{1 - \delta} \right)$$

Where:

$$\eta = \left[p - \alpha_r - S_t \alpha_{rS} - \beta \left(\frac{\delta}{1 - \delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1 - d}{d} \right) + \beta \left(\frac{\delta(1 - d)}{1 - \delta(1 - d)} \right) \alpha_{rS} \left(\frac{1 - d}{d} \right) \right] \frac{1}{e}$$

For all other parameter values, the exposure subsidy is equally as good as the use subsidy (i.e. agents would make the same choices and social welfare would be the same under both regimes).

Observe that:

- If $\beta = 1$ (i.e. no present bias), then the exposure subsidy is equally good to the use subsidy for all parameter values.
- As β declines, the range of values for which an exposure subsidy is superior to a use subsidy widens.

If the optimal policy is an exposure subsidy, then the optimal subsidy duration k^* is a

decreasing function of the return to exposure (expressed by the exposure parameter α_{rS}):

$$\frac{\partial k^*}{\partial \alpha_{rS}} = \underbrace{\frac{1}{\log(1-d)}}_{(-)} \underbrace{\frac{1}{\frac{1-d}{d} - S^*}}_{(+)} \underbrace{\frac{1-\delta(1-d)}{1-\delta}}_{(+)} \underbrace{\frac{\alpha_r}{\alpha_{rS}^2}}_{(-)} \underbrace{(-1)}_{(-)} < 0 \quad (23)$$

The first expression is negative because $d \in (0, 1)$, the second expression is positive because $\frac{1-d}{d} > S^*$ if the optimal policy is an exposure subsidy, the third expression is positive because $d \in (0, 1)$ and $\delta \in (0, 1)$, and the fourth expression is negative because $\alpha_r < 0$. The intuition is that a larger return to exposure α_{rS} reduces the exposure threshold S^* at which an agent would choose to use the good on her own, which reduces the number of periods needed to achieve the exposure threshold.

C.3 Model with present bias and information mechanism

Intuition. With present bias and the information mechanism, we compare an exposure subsidy to a purchase subsidy and a perpetual use subsidy with present value equal to the present value of generating the externality in every subsequent period. With magnitudes calibrated by the externality, an exposure subsidy can be better than a perpetual use subsidy when the perpetual use subsidy is insufficient to induce a present-biased agent to use the good because so much of the subsidy is heavily discounted in the distant future. If a sufficiently large portion of the exposure subsidy is delivered immediately, then it would induce an uninformed agent to use the good (by concentrating the subsidy in the first period that is not heavily discounted) even though the agent would not be induced by the perpetual use subsidy. In that case, the exposure subsidy would also be superior to a purchase subsidy, which would induce a smaller fraction of agents to learn their match quality and would miss out on the positive externality that those agents would have generated.

Agents. There is a population of agents of measure one. Each agent chooses in each

period whether or not to use a good to maximize the discounted stream of expected utility. If the agent does not use the good, then utility is zero. If the agent uses the good, then the agent derives utility from the direct net benefit of using the good (which could be negative) and from a subsidy σ set by a policymaker. If the agent is using the good for the first time, then the agent also pays a price p . The agent is present-biased in the sense that the discount applied between the current period and the next period is larger than the discount applied between any other two consecutive periods (quasi-hyperbolic discounting or beta-delta discounting). The discounted stream of expected utility in period t is:

$$U_t = \max_{r_t \in \{0,1\}} \int_{-\infty}^{\infty} u_t \, dF_t(\theta) + \beta \sum_{j=1}^{\infty} \delta^j \int_{-\infty}^{\infty} u_{t+j} \, dF_t(\theta) \quad (24)$$

where $r \in \{0,1\}$ is a discrete choice to either use the good or not, $\delta \in (0,1)$ is the agent's time discount factor, and $\beta \in [0,1]$ expresses the extent of the agent's present bias.

Utility in period t takes the form:

$$u_t = u(r_t, \theta_i) = r_t \alpha_r + r_t \theta_i \alpha_{r\theta} + r_t \sigma_t - r_t p \, \mathbb{I}[\forall j < 0 : r_{t+j} = 0] \quad (25)$$

where θ is match quality and \mathbb{I} is an indicator function equal to one if the argument is true and zero if it is false. The population comprises agents with low and high match quality between the agent and the good. We assume that a fraction q of agents have low match quality, and $1 - q$ have high match quality, such that the population distribution of match quality can be expressed with the following probability mass function f with $q \in (0,1)$:

$$f(\theta) = \begin{cases} q & \text{if } \theta = 0 \\ 1 - q & \text{if } \theta = 1 \end{cases} \quad (26)$$

We assume the signal is either fully informative or totally uninformative, such that the

distribution of signals can be expressed with the following probability mass function g with $\gamma \in (0, 1)$:

$$g(\omega_t|\theta_i) = \begin{cases} \gamma & \text{if } \omega_t = -1 \\ 1 - \gamma & \text{if } \omega_t = \theta_i \end{cases} \quad (27)$$

Social planner. A social planner chooses a sequence of subsidies to maximize social welfare, which consists of the sum of the agent's utility and externalities net of subsidies. Unlike the agent, the social planner uses a consistent discount rate of δ , i.e. even though the agent is present-biased the social planner is not. Each period the good is used, it generates a positive externality e . We assume the sequence of subsidies is constrained to be some positive value σ for some number of periods k and, if k is finite, zero thereafter. In other words, the social planner can choose the subsidy level σ and duration k but cannot tailor the subsidy to be a different magnitude in each individual period. The social planner thus chooses the subsidy level and duration to maximize welfare:

$$\max_{\sigma, k} \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (u_{t+j} + r_{t+j}e) dF_t(\theta) - \sum_{j=0}^{k-1} \delta^j r_{t+j}(\sigma) \quad (28)$$

where F is the cumulative distribution function corresponding to f .

We assume that the social planner follows through on all promises made at the time the agent first uses the good, i.e. there are no obstacles to credibly committing to a subsidy level and duration.

We assume:

- The net private benefit to an agent who knows she has high match quality is positive:

$$\alpha_r + \alpha_{r\theta} > 0$$

- The net social benefit to a low match quality agent is negative: $\alpha_r + e < 0$

- The net private benefit to an agent who does not know her match quality is negative:

$$\alpha_r + \alpha_{r\theta}(1 - q) + (1 - q)(1 - \gamma)\frac{\beta\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta}) < 0$$

- The net social benefit for an agent with an unknown match quality is positive: $\alpha_r +$

$$\alpha_{r\theta}(1 - q) + e + (1 - q)(1 - \gamma)\frac{\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta} + e) > 0$$

Solution for the agents. If $k = 1$ and $p = 0$, then expected utility at time t is:

$$\begin{aligned} U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} \int_{-\infty}^{\infty} r_t(\alpha_r + \theta_i \alpha_{r\theta} + \sigma) dF_t(\theta) + \beta \sum_{j=1}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) \\ &= \max \left\{ \alpha_r + \alpha_{r\theta}(1 - q) + \sigma + (1 - q)(1 - \gamma)\frac{\beta\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta}), 0 \right\} \end{aligned}$$

Pooling equilibrium. Define $\hat{\sigma}$ as the minimum subsidy such that an agent who knows she has low match quality chooses to use the good when $k = 1$ and $p = 0$: $\hat{\sigma} = -\alpha_r$. If the agent has not previously used the good (i.e. the price p must be paid) and $\sigma \geq \hat{\sigma}$ (i.e. an agent who knows she has low match quality behaves the same way as an agent with unknown match quality), then expected utility at time t is:

$$\begin{aligned} U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} r_t(\alpha_r + \theta_i \alpha_{r\theta} + \sigma - p) + \beta \sum_{j=1}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) + \beta \sum_{j=1}^{k-1} \delta^j r_{t+j} \sigma \\ &= \max \left\{ 0, -p + \left(1 + \beta \frac{\delta - \delta^k}{1 - \delta} \right) (\alpha_r + (1 - q)\alpha_{r\theta} + \sigma) \right. \\ &\quad \left. + (1 - q)(1 - \gamma^k) \frac{\beta\delta^k}{1 - \delta} (\alpha_r + \alpha_{r\theta}) \right\} \end{aligned}$$

Separating equilibrium. Define $\tilde{\sigma}$ as the minimum subsidy such that an uninformed agent chooses to use the good when $k = 1$ and $p = 0$:

$$\tilde{\sigma} = -\alpha_r - \alpha_{r\theta}(1 - q) - (1 - q)(1 - \gamma)\frac{\beta\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta})$$

If the agent has not previously used the good (i.e. the price p must be paid) and $\tilde{\sigma} < \sigma < \hat{\sigma}$

(i.e. an agent who knows she has low match quality behaves differently from an agent with unknown match quality), then expected utility at time t is:

$$\begin{aligned}
U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} r_t(\alpha_r + \theta_i \alpha_{r\theta} + \sigma - p) + \beta \sum_{j=1}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) + \beta \sum_{j=1}^{k-1} \delta^j r_{t+j} \sigma \\
&= \max \left\{ 0, \underbrace{-p + (1-q) \left(1 + \beta \frac{\delta - \delta^k}{1 - \delta} \right) (\alpha_r + \alpha_{r\theta} + \sigma)}_{\text{utility of high match quality during first } k \text{ periods}} \right. \\
&\quad + \underbrace{(q) \left(1 + \beta \frac{\delta \gamma - \delta^k \gamma^k}{1 - \delta \gamma} \right) (\alpha_r + \sigma)}_{\text{utility of low match quality during first } k \text{ periods}} \\
&\quad \left. + \underbrace{(1-q)(1-\gamma^k) \frac{\beta \delta^k}{1 - \delta} (\alpha_r + \alpha_{r\theta})}_{\text{utility of known high match quality from period } k \text{ onward}} \right\}
\end{aligned}$$

There are three possibilities: (1) the agent learns she has high match quality, (2) the agent learns she has low match quality, (3) the agent does not learn her match quality. If she learns she has low match quality, then she immediately disadopts the good. If she does not learn her match quality, then she disadopts when the subsidy ends after k periods. If she learns she has high match quality, then she continues using the good in perpetuity even after the subsidy ends.

Solution for the social planner. We compare:

- A use subsidy with $\sigma = e$ and $k = \infty$
- A purchase subsidy with the same present value, with $k = 1$
- An exposure subsidy with the same present value, that minimally supports a separating equilibrium, i.e. the smallest k that achieves $\sigma < -\alpha_r$

For each subsidy, we set the present discounted value equal to $\frac{1}{1-\delta}e$. So:

$$\begin{aligned}\sigma_{use}^* &= e \\ \sigma_{pur}^* &= \frac{1}{1-\delta}e \\ \sigma_{exp}^* &= \frac{1}{1-\delta^{k_{exp}^*}}e\end{aligned}$$

We derive k_{exp}^* (the duration of the exposure subsidy) as follows:

$$\begin{aligned}-\alpha_r &= \frac{1}{1-\delta^{\tilde{k}}}e \\ 1-\delta^{\tilde{k}} &= \frac{e}{-\alpha_r} \\ \delta^{\tilde{k}} &= \frac{-e-\alpha_r}{-\alpha_r} \\ \tilde{k} \log(\delta) &= \log(-e-\alpha_r) - \log(-\alpha_r) \\ k_{exp}^* &= \text{ceiling}\left(\frac{\log(-e-\alpha_r) - \log(-\alpha_r)}{\log(\delta)}\right)\end{aligned}$$

Where the last step is taken so that k_{exp}^* is the whole number that minimally achieves a separating equilibrium (where agents who know they have low match quality choose not to use the good).

Use subsidy. We know that the use subsidy supports a separating equilibrium because the utility of an agent who knows they have low match quality is negative ($\alpha_r + \sigma = \alpha_r + e < 0$). Using the indifference condition from the separating equilibrium solution for the agents, we see that an agent with unknown match quality is willing to use the good for the first time under a use subsidy if:

$$p < \underbrace{\alpha_r + (1-q)\alpha_{r\theta} + \sigma}_{\text{utility during first period}} + \underbrace{(1-q)\left(\frac{\beta\delta}{1-\delta}\right)(\alpha_r + \alpha_{r\theta} + \sigma)}_{\text{utility of high match quality}} + \underbrace{(q)\left(\frac{\beta\delta\gamma}{1-\delta\gamma}\right)(\alpha_r + \sigma)}_{\text{utility of low match quality}} = U_{use}^*$$

Purchase subsidy. Using the indifference condition from the separating equilibrium solution for the agents, we see that an agent with unknown match quality is willing to use the good for the first time under a purchase subsidy if:

$$p < \underbrace{\alpha_r + (1 - q)\alpha_{r\theta} + \sigma}_{\text{utility during first period}} + \underbrace{(1 - q)(1 - \gamma)\frac{\beta\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta})}_{\text{utility of high match quality after the first period}} = U_{pur}^*$$

Exposure subsidy. Using the indifference condition from the separating equilibrium solution for the agents, we see that an agent with unknown match quality is willing to use the good for the first time under an exposure subsidy if:

$$\begin{aligned} p &< \underbrace{\alpha_r + (1 - q)\alpha_{r\theta} + \sigma}_{\text{utility during first period}} \\ &\quad + \underbrace{(1 - q)\left(\beta\frac{\delta - \delta^k}{1 - \delta}\right)(\alpha_r + \alpha_{r\theta} + \sigma)}_{\text{high match quality during first } k \text{ periods}} \\ &\quad + \underbrace{(q)\left(\beta\frac{\delta\gamma - \delta^k\gamma^k}{1 - \delta}\right)(\alpha_r + \sigma)}_{\text{low match quality during first } k \text{ periods}} \\ &\quad + \underbrace{(1 - q)(1 - \gamma)\frac{\beta\delta^k}{1 - \delta}(\alpha_r + \alpha_{r\theta})}_{\text{high match quality after } k \text{ periods}} = U_{exp}^* \end{aligned}$$

An exposure subsidy is superior to a use subsidy if $U_{exp}^* > p > U_{use}^*$ because in that case the exposure subsidy induces use and the use subsidy does not.

An exposure subsidy is superior to a purchase subsidy if $U_{exp}^* > p$. (This condition implies that $U_{pur}^* > p$ because the value of the subsidy is concentrated in the first period with the purchase subsidy.) In that case, a larger fraction of high match quality agents learn their match quality and continue using the good indefinitely.

C.4 Model with liquidity constraint and taste/ability mechanism

Intuition. With a liquidity constraint and the taste/ability mechanism, the social planner chooses the minimal exposure subsidy duration k such that the agent, having built up a sufficient exposure stock, would continue using the good on her own after the subsidy is removed. The social planner chooses the exposure subsidy level σ such that the present value of the subsidy matches the present value of the externalities in perpetuity. An exposure subsidy chosen this way can be better than a perpetual use subsidy if the portion of the perpetual use subsidy delivered in the first period is inadequate to overcome the liquidity constraint, thus resulting in nonadoption. An exposure subsidy can be better than a purchase subsidy because under the purchase subsidy the agent would never attain sufficient exposure to continue using the good on her own, thus resulting in adoption in the first period and subsequent disadoption.

Agents. There is a population of identical agents of measure one. Each agent chooses in each period whether or not to use a good to maximize the discounted stream of expected utility. If the agent does not use the good, then utility is zero. If the agent uses the good, then the agent derives utility from the direct net benefit of using the good (which could be negative) and from a subsidy σ set by a policymaker. If the agent is using the good for the first time, then the agent also pays a price p . The agent is liquidity-constrained in the sense that the agent cannot make decisions that would result in period utility falling below some lower bound. The discounted stream of utility in period t is:

$$U_t = \max_{r_t \in \{0,1\}} \sum_{j=0}^{\infty} \delta^j u_{t+j} \quad (29)$$

$$s.t. \quad \forall j \quad u_{t+j} \geq \underline{u} \quad (30)$$

where $r \in \{0,1\}$ is a discrete choice to either use the good or not, $\delta \in (0,1)$ is the agent's

time discount factor, and $\underline{u} < 0$ is the lower bound on period utility¹⁰.

Utility in period t takes the form:

$$u_t = u(r_t, S_t) = r_t \alpha_r + r_t S_t \alpha_{rS} + r_t \sigma_t - r_t p \mathbb{I}[\forall j < 0 : r_{t+j} = 0] \quad (31)$$

where $S \geq 0$ is an exposure stock indicating taste or ability and \mathbb{I} is an indicator function equal to one if the argument is true and zero if it is false. The exposure stock evolves according to the following law of motion:

$$S_{t+1} = (1 - d)(S_t + r_t) \quad (32)$$

where $d \in (0, 1)$ is a depreciation parameter.

We assume:

- With zero subsidy and zero exposure ($\sigma = 0$ and $S_t = 0$), the liquidity constraint is binding: $\alpha_r - p < \underline{u}$

Social planner. A social planner chooses a sequence of subsidies to maximize social welfare, which consists of the sum of the agent's utility and externalities net of subsidies. Each period the good is used, it generates a positive externality e . We assume the sequence of subsidies is constrained to be some positive value σ for some number of periods k and, if k is finite, zero thereafter. In other words, the social planner can choose the subsidy level σ and duration k but cannot tailor the subsidy to be a different magnitude in each individual

¹⁰For a similar modeling approach, see Zeldes (1989). In that model, a liquidity constraint is modeled as a lower bound on assets. We express a similar idea with a lower bound on period utility because we do not model assets explicitly.

period. The social planner thus chooses the subsidy level and duration to maximize welfare:

$$\max_{\sigma, k} \sum_{j=0}^{\infty} \delta^j (u_{t+j} + r_{t+j}e) - \sum_{j=0}^{k-1} \delta^j r_{t+j}(\sigma) \quad (33)$$

We assume that the social planner follows through on all promises made at the time the agent first uses the good, i.e. there are no obstacles to credibly committing to a subsidy level and duration.

Solution for the agents. If the agent has not previously used the good (i.e. $S_t = 0$ and the price p must be paid), then expected utility at time t is:

$$\begin{aligned} U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} r_t \left(\alpha_r + S_t \alpha_{rS} + \sigma - p \right) + \sum_{j=1}^{\infty} \delta^j (r_{t+j} \alpha_r + r_{t+j} S_{t+j} \alpha_{rS}) + \sum_{j=1}^{k-1} \delta^j r_{t+j} \sigma \\ &= \max \left\{ \left(\alpha_r + S_t \alpha_{rS} + \sigma - p \right) + \underbrace{\left(\frac{\delta - \delta^k}{1 - \delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} + \sigma \right)}_{r_{t+j}=1 \text{ for } j < k \text{ and } r_{t+j}=0 \text{ for } j \geq k} \right. \\ &\quad \left. - \underbrace{\left(\frac{\delta(1-d) - \delta^k(1-d)^k}{1 - \delta(1-d)} \right) \alpha_{rS} \left(\frac{1-d}{d} \right)}_{r_{t+j}=1 \text{ for } j \geq 0} \right. \\ &\quad \left. - \underbrace{\left(\frac{\delta(1-d)}{1 - \delta(1-d)} \right) \alpha_{rS} \left(\frac{1-d}{d} \right) + \left(\frac{\delta - \delta^k}{1 - \delta} \right) \sigma}_{r_{t+j}=1 \text{ for } j \geq 0} \right. \\ &\quad \left. \underbrace{0}_{r_{t+j}=0 \text{ for } j \geq 0} \right\} \end{aligned}$$

There are three possibilities: (1) the agent may use the good forever (perpetual use), (2) the agent may use the good until the subsidy is removed (disadoption), or (3) the agent may decline to use the good (non-adoption). In order for the agent to use the good even once, utility in the first period the agent uses the good must exceed the lower bound: $\alpha_r + \sigma - p \geq \underline{u}$. If that criterion is not met, then non-adoption is the only feasible choice for the agent.

Solution for the social planner. A policy that results in disadoption cannot be

optimal. Proof is by contradiction. Suppose that (σ, k) were optimal and that it resulted in disadoption (so k is finite). If the policy is optimal, then $e > \sigma$. (If that were not true then a policy with subsidy equal to zero would be better.) Furthermore, extending the subsidy by one day would result in use for one more day with positive net welfare because period utility is increasing in the exposure stock and $e > \sigma$. So a policy of $(\sigma, k + 1)$ is strictly better than (σ, k) . That contradicts the assumption that (σ, k) is optimal.

So the optimal policy either results in perpetual use or non-adoption.

First, we find the exposure threshold at which an agent would continue using the good if the good had already been used in prior periods:

$$S^* = -\left(\frac{1 - \delta(1 - d)}{1 - \delta}\right) \frac{\alpha_r}{\alpha_{rS}} - \left(\frac{\delta(1 - d)}{1 - \delta}\right)$$

Use subsidy. If $S^* \geq \frac{1-d}{d}$, then perpetual use can only be achieved with an ongoing use subsidy with $k = \infty$ and $\sigma = e$ is optimal.

The agent uses the good in perpetuity if:

$$\left(\alpha_r + S_t \alpha_{rS} + e - p\right) + \left(\frac{\delta}{1 - \delta}\right) \left(\alpha_r + \alpha_{rS} \frac{1 - d}{d}\right) - \left(\frac{\delta(1 - d)}{1 - \delta(1 - d)}\right) \alpha_{rS} \left(\frac{1 - d}{d}\right) + \left(\frac{\delta}{1 - \delta}\right) e > 0$$

And:

$$\alpha_r + S_t \alpha_{rS} + e - p \geq \underline{u}$$

Exposure subsidy. If $S^* > 0$ and $S^* < \frac{1-d}{d}$, then perpetual use can be achieved with a subsidy of finite duration. The minimum number of periods required for the agent to reach

the exposure threshold (and continue using the good without a subsidy) is:

$$k^* = \text{ceiling} \left(\frac{\log(\frac{1-d}{d} - S^*) - \log(\frac{1-d}{d} - S_t)}{\log(1-d)} \right)$$

We consider the following exposure subsidy, which has the same discounted value as the externalities in perpetuity:

$$\sigma^* = \frac{1}{1 - \delta^{k^*}} e$$

This exposure subsidy has the effect of concentrating the subsidies in a shorter time interval. Because the agent is liquidity-constrained, subsidies in the first period may relax a binding constraint that would otherwise prevent the agent from adopting the good.

The agent uses the good in perpetuity if:

$$\begin{aligned} & \left(\alpha_r + S_t \alpha_{rS} + \frac{1}{1 - \delta^{k^*}} e - p \right) + \left(\frac{\delta}{1 - \delta} \right) \left(\alpha_r + \alpha_{rS} \frac{1-d}{d} \right) \\ & - \left(\frac{\delta(1-d)}{1 - \delta(1-d)} \right) \alpha_{rS} \left(\frac{1-d}{d} \right) + \left(\frac{\delta - \delta^k}{1 - \delta} \right) \frac{1}{1 - \delta^{k^*}} e > 0 \end{aligned}$$

And:

$$\alpha_r + S_t \alpha_{rS} + \frac{1}{1 - \delta^{k^*}} e - p \geq \underline{u}$$

The first condition is that the discounted stream of utility must be positive, and it is satisfied for the exposure subsidy if and only if it is satisfied for the use subsidy (because the exposure subsidy has the same present value as the use subsidy). The second condition may be satisfied for the exposure subsidy even when it is not satisfied for the use subsidy.

Thus, the exposure subsidy ($\sigma^* = \frac{1}{1-\delta^{k^*}}e$) is superior to a use subsidy ($\sigma = e$) if:

$$\frac{1}{1-\delta^{k^*}}e > \underline{u} + p - \alpha_r - S_t \alpha_{rS} > e$$

I.e., the exposure subsidy is large enough to boost period utility above the lower bound, but the use subsidy is not large enough to boost period utility above the lower bound.

If the optimal policy is an exposure subsidy, then the optimal subsidy duration k^* is a decreasing function of the return to exposure (expressed by the exposure parameter α_{rS}):

$$\frac{\partial k^*}{\partial \alpha_{rS}} = \underbrace{\frac{1}{\log(1-d)}}_{(-)} \underbrace{\frac{1}{\frac{1-d}{d} - S^*}}_{(+)} \underbrace{\frac{1-\delta(1-d)}{1-\delta}}_{(+)} \underbrace{\frac{\alpha_r}{\alpha_{rS}^2}}_{(-)} \underbrace{(-1)}_{(-)} < 0 \quad (34)$$

The first expression is negative because $d \in (0, 1)$, the second expression is positive because $\frac{1-d}{d} > S^*$ if the optimal policy is an exposure subsidy, the third expression is positive because $d \in (0, 1)$ and $\delta \in (0, 1)$, and the fourth expression is negative because $\alpha_r < 0$. The intuition is that a larger return to exposure α_{rS} reduces the exposure threshold S^* at which an agent would choose to use the good on her own, which reduces the number of periods needed to achieve the exposure threshold.

C.5 Model with liquidity constraint and information mechanism

Intuition. With a liquidity constraint and the information mechanism, we compare an exposure subsidy to a purchase subsidy and a perpetual use subsidy with present value equal to the present value of generating the externality in every subsequent period. With magnitudes calibrated by the externality, an exposure subsidy can be better than a perpetual use subsidy when the perpetual use subsidy is insufficient to induce a present-biased agent to use the good because so much of the subsidy is heavily discounted in the distant future.

If a sufficiently large portion of the exposure subsidy is delivered immediately, then it would induce an uninformed agent to use the good (by overcoming the liquidity constraint) even though the agent would not be induced by the perpetual use subsidy. In that case, the exposure subsidy would also be superior to a purchase subsidy, which would induce a smaller fraction of agents to learn their match quality and would miss out on the positive externality that those agents would have generated.

Agents. There is a population of agents of measure one. Each agent chooses in each period whether or not to use a good to maximize the discounted stream of expected utility. If the agent does not use the good, then utility is zero. If the agent uses the good, then the agent derives utility from the direct net benefit of using the good (which could be negative) and from a subsidy σ set by a policymaker. If the agent is using the good for the first time, then the agent also pays a price p . The agent is liquidity-constrained in the sense that the agent cannot make decisions that would result in period utility falling below some lower bound. The discounted stream of expected utility in period t is:

$$U_t = \max_{r_t \in \{0,1\}} \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} u_{t+j} dF_t(\theta) \quad (35)$$

$$s.t. \quad \forall j \quad u_{t+j} \geq \underline{u} \quad (36)$$

where $r \in \{0,1\}$ is a discrete choice to either use the good or not, $\delta \in (0,1)$ is the agent's time discount factor, and $\underline{u} < 0$ is the lower bound on period utility.

Utility in period t takes the form:

$$u_t = u(r_t, \theta_i) = r_t \alpha_r + r_t \theta_i \alpha_{r\theta} + r_t \sigma_t - r_t p \mathbb{I}[\forall j < 0 : r_{t+j} = 0] \quad (37)$$

where θ is match quality and \mathbb{I} is an indicator function equal to one if the argument is true and zero if it is false. The population comprises agents with low and high match quality

between the agent and the good. We assume that a fraction q of agents have low match quality, and $1 - q$ have high match quality, such that the population distribution of match quality can be expressed with the following probability mass function f with $q \in (0, 1)$:

$$f(\theta) = \begin{cases} q & \text{if } \theta = 0 \\ 1 - q & \text{if } \theta = 1 \end{cases} \quad (38)$$

We assume the signal is either fully informative or totally uninformative, such that the distribution of signals can be expressed with the following probability mass function g with $\gamma \in (0, 1)$:

$$g(\omega_t | \theta_i) = \begin{cases} \gamma & \text{if } \omega_t = -1 \\ 1 - \gamma & \text{if } \omega_t = \theta_i \end{cases} \quad (39)$$

Social planner. A social planner chooses a sequence of subsidies to maximize social welfare, which consists of the sum of the agent's utility and externalities net of subsidies. Each period the good is used, it generates a positive externality e . We assume the sequence of subsidies is constrained to be some positive value σ for some number of periods k and, if k is finite, zero thereafter. In other words, the social planner can choose the subsidy level σ and duration k but cannot tailor the subsidy to be a different magnitude in each individual period. The social planner thus chooses the subsidy level and duration to maximize welfare:

$$\max_{\sigma, k} \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (u_{t+j} + r_{t+j}e) dF_t(\theta) - \sum_{j=0}^{k-1} \delta^j r_{t+j}(\sigma) \quad (40)$$

where F is the cumulative distribution function corresponding to f .

We assume that the social planner follows through on all promises made at the time the agent first uses the good, i.e. there are no obstacles to credibly committing to a subsidy

level and duration.

We assume:

- The net private benefit to an agent who knows she has high match quality is positive:

$$\alpha_r + \alpha_{r\theta} > 0$$

- The net social benefit for a low match quality agent is negative: $\alpha_r + e < 0$

- The net private benefit to an agent who does not know her match quality is negative:

$$\alpha_r + \alpha_{r\theta}(1 - q) + (1 - q)(1 - \gamma)\frac{\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta}) < 0$$

- The net social benefit for an agent who does not know her match quality is positive:

$$\alpha_r + \alpha_{r\theta}(1 - q) + e + (1 - q)(1 - \gamma)\frac{\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta} + e) > 0$$

Solution for the agents. In order for the agent to use the good even once, utility in the first period the agent uses the good must exceed the lower bound: $\alpha_r + \sigma - p \geq \underline{u}$. For an agent who does not know her match quality, the liquidity constraint binds as if she were known to have low match quality. If that criterion is not met, then non-adoption is the only feasible choice for the agent.

If $k = 1$ and $p = 0$, then expected utility at time t is:

$$\begin{aligned} U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} r_t \sigma + \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) \\ &= \max \left\{ \alpha_r + \alpha_{r\theta}(1 - q) + \sigma + (1 - q)(1 - \gamma)\frac{\delta}{1 - \delta}(\alpha_r + \alpha_{r\theta}), 0 \right\} \end{aligned}$$

Pooling equilibrium. Define $\hat{\sigma}$ as the minimum subsidy such that an agent who knows she has low match quality chooses to use the good when $k = 1$ and $p = 0$: $\hat{\sigma} = -\alpha_r$. If the agent has not previously used the good (i.e. the price p must be paid) and $\sigma \geq \hat{\sigma}$ (i.e. an agent who knows she has low match quality behaves the same way as an agent with unknown

match quality), then expected utility at time t is:

$$\begin{aligned}
U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} -r_t p + \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) + \sum_{j=0}^{k-1} \delta^j r_{t+j} \sigma \\
&= \max \left\{ 0, \quad -p + \frac{1 - \delta^k}{1 - \delta} \left(\alpha_r + (1 - q) \alpha_{r\theta} + \sigma \right) \right. \\
&\quad \left. + (1 - q)(1 - \gamma^k) \frac{\delta^k}{1 - \delta} \left(\alpha_r + \alpha_{r\theta} \right) \right\}
\end{aligned}$$

Separating equilibrium. Define $\tilde{\sigma}$ as the minimum subsidy such that an uninformed agent chooses to use the good when $k = 1$ and $p = 0$:

$$\tilde{\sigma} = -\alpha_r - \alpha_{r\theta}(1 - q) - (1 - q)(1 - \gamma) \frac{\delta}{1 - \delta} (\alpha_r + \alpha_{r\theta})$$

If the agent has not previously used the good (i.e. the price p must be paid) and $\tilde{\sigma} < \sigma < \hat{\sigma}$ (i.e. an agent who knows she has low match quality behaves differently from an agent with unknown match quality), then expected utility at time t is:

$$\begin{aligned}
U_t(\sigma, k) &= \max_{r_t \in \{0,1\}} -r_t p + \sum_{j=0}^{\infty} \delta^j \int_{-\infty}^{\infty} (r_{t+j} \alpha_r + r_{t+j} \theta_i \alpha_{r\theta}) dF_t(\theta) + \sum_{j=0}^{k-1} \delta^j r_{t+j} \sigma \\
&= \max \left\{ 0, \quad -p + \underbrace{\left((1 - q) \frac{1 - \delta^k}{1 - \delta} \left(\alpha_r + \alpha_{r\theta} + \sigma \right) \right)}_{\text{utility of high match quality during first } k \text{ periods}} \right. \\
&\quad + \underbrace{\left((q) \frac{1 - \delta^k \gamma^k}{1 - \delta \gamma} \left(\alpha_r + \sigma \right) \right)}_{\text{utility of low match quality during first } k \text{ periods}} \\
&\quad \left. + \underbrace{\left((1 - q)(1 - \gamma^k) \frac{\delta^k}{1 - \delta} \left(\alpha_r + \alpha_{r\theta} \right) \right)}_{\text{utility of known high match quality from period } k \text{ onward}} \right\}
\end{aligned}$$

There are three possibilities: (1) the agent learns she has high match quality, (2) the agent learns she has low match quality, (3) the agent does not learn her match quality. If she learns she has low match quality, then she immediately disadopts the good. If she does

not learn her match quality, then she disadopts when the subsidy ends after k periods. If she learns she has high match quality, then she continues using the good in perpetuity even after the subsidy ends.

Solution for the social planner. Using the indifference condition from the separating equilibrium solution for the agents, we see that an agent with unknown match quality is willing to use the good for the first time under an exposure subsidy if:

$$\begin{aligned}
 p < & \underbrace{\alpha_r + (1 - q)\alpha_{r\theta} + \sigma}_{\text{utility during first period}} \\
 & + \underbrace{(1 - q)\left(\frac{\delta - \delta^k}{1 - \delta}\right)(\alpha_r + \alpha_{r\theta} + \sigma)}_{\text{high match quality during first } k \text{ periods}} \\
 & + \underbrace{(q)\left(\frac{\delta\gamma - \delta^k\gamma^k}{1 - \delta}\right)(\alpha_r + \sigma)}_{\text{low match quality during first } k \text{ periods}} \\
 & + \underbrace{(1 - q)(1 - \gamma)\frac{\delta^k}{1 - \delta}(\alpha_r + \alpha_{r\theta})}_{\text{high match quality after } k \text{ periods}}
 \end{aligned}$$

And:

$$\alpha_r + \sigma - p \geq \underline{u}$$

The first condition is that the discounted stream of utility must be positive, and it is satisfied for the exposure subsidy under the same conditions as for the purchase subsidy and the use subsidy. This is because the subsidies have been constructed with equal present value, and their only influence on the discounted stream of utility is through present value.

We compare:

- A use subsidy with $\sigma = e$ and $k = \infty$

- A purchase subsidy with the same present value, with $k = 1$
- An exposure subsidy with the same present value, that minimally satisfies the second criterion (liquidity constraint), i.e. the largest k that achieves $\alpha_r + \sigma - p \geq \underline{u}$

For each subsidy, we set the present discounted value equal to $\frac{1}{1-\delta}e$. So:

$$\begin{aligned}\sigma_{use}^* &= e \\ \sigma_{pur}^* &= \frac{1}{1-\delta}e \\ \sigma_{exp}^* &= \frac{1}{1-\delta^{k_{exp}^*}}e\end{aligned}$$

If $\alpha_r + e - p \geq \underline{u}$ then a use subsidy with $k = \infty$ and $\sigma = e$ is optimal.

Assuming $\alpha_r + e - p < \underline{u}$, we derive k_{exp}^* (the duration of the exposure subsidy) as follows:

$$\begin{aligned}\alpha_r + \tilde{\sigma} - p &= \underline{u} \\ \alpha_r + \frac{1}{1-\delta^{\tilde{k}}}e - p &= \underline{u} \\ \frac{1}{1-\delta^{\tilde{k}}}e &= \underline{u} + p - \alpha_r \\ \frac{e}{\underline{u} + p - \alpha_r} &= 1 - \delta^{\tilde{k}} \\ \delta^{\tilde{k}} &= \frac{\underline{u} + p - \alpha_r - e}{\underline{u} + p - \alpha_r} \\ \tilde{k} &= \frac{\log(\underline{u} + p - \alpha_r - e) - \log(\underline{u} + p - \alpha_r)}{\log(\delta)} \\ k_{exp}^* &= \text{floor}\left(\frac{\log(\underline{u} + p - \alpha_r - e) - \log(\underline{u} + p - \alpha_r)}{\log(\delta)}\right)\end{aligned}$$

Where the last step is taken so that k_{exp}^* is the whole number that minimally satisfies the liquidity constraint (where the utility in period t exceeds \underline{u}).

An exposure subsidy defined in this way is superior to a purchase subsidy because a larger fraction of high match quality agents learn their match quality and continue using the

good indefinitely.

There exists some subsidy level σ that (a) satisfies the liquidity constraint and (b) supports a separating equilibrium if and only if $p < -\underline{u}$.

Assume $p < -\underline{u}$. Then:

$$p < -\underline{u}$$

$$p + \underline{u} < 0$$

$$p + \underline{u} - \alpha_r < -\alpha_r$$

By continuity, $\exists \sigma$ such that:

$$p + \underline{u} - \alpha_r < \sigma < -\alpha_r$$

The first inequality ensures that the liquidity constraint is satisfied. The second inequality ensures that a separating equilibrium is supportable.

Going in the opposite direction, assume that there exists a subsidy that (a) satisfies the liquidity constraint and (b) supports a separating equilibrium. Then:

$$p + \underline{u} - \alpha_r < \sigma < -\alpha_r$$

$$p + \underline{u} < 0$$

$$p < -\underline{u}$$

If $p > -\underline{u}$, then the solution is a pooling equilibrium, and the solution trades off between subsidy “wasted” on agents who know they have low match quality and subsidy “spent” on agents who learn they have high match quality, along the lines of the solution to the model with administrative costs and information.

Appendix D Retrospective policy analysis (for online publication)

This section compares the relative effectiveness of the specific subsidies offered to promote the persistent use of water-efficient technologies in the field experiment. In other words, it considers whether a program manager with a fixed budget and a goal of maximizing the number of households using the technology at endline (2016) would have been better off spending an incremental dollar on the bonus for keeping the technology in place through the first audit at four months (exposure subsidy) or on the free installation (purchase subsidy).

To be concrete, we consider how the program manager could use an additional \$1000. If the program manager spent \$1000 on additional no-bonus installations, then the expected number of additional low-flow fixtures in use after 16 months would be 52 fixtures:

$$\underbrace{\frac{0.595}{0.869}}_{\text{No-bonus retention rate}} \times \underbrace{\$1000}_{\text{Budget}} / \underbrace{\$13.12}_{\text{Cost of installation}} = 52.2 \quad (41)$$

The cost of installing three low-flow fixtures is the sum of three components: (1) the price in San Jose for a bundle of one low-flow showerhead and two faucet aerators (\$22.49), (2) the estimated cost of additional components (fixtures and adapters) required for the low-flow fixtures to operate (\$14.59), and (3) the local cost of a plumber for installing these items (\$2.28).¹¹ The cost of installing one fixture is the total cost of installing three fixtures divided by three (\$13.12 = \$39.36 / 3).

In contrast, if the program manager spent \$1000 on subsidies of the same size and timing as in the bonus group to households where the technology was already installed but were not yet being offered a bonus, then the expected number of additional low-flow fixtures in use after 16 months would be 3.3 fixtures.

¹¹The bundle was not sold in the communities, but it was available in the capital city of San Jose, approximately 100 kilometers from the nearest community in the study.

$$\underbrace{\frac{0.640 - 0.595}{0.841}}_{\text{New fixtures per fixture receiving bonus}} \times \underbrace{\$1000}_{\text{Budget}} / \underbrace{\$16.4}_{\text{Average bonus per fixture}} = 3.3 \quad (42)$$

The components of the calculation for new fixtures per fixture receiving the bonus are from Table 2. Each household in the cash-bonus group was offered 20,000 colones (approximately \$36) if all installed low-flow fixtures were in use during the 2015 audit. The bonus payment was equal to the fraction of low-flow fixtures in use times the maximum possible bonus. For example, if two fixtures were installed in a household, and only one fixture was in use during the 2015 audit, then that household was paid 10,000 colones (20,000 colones x 1 fixture in use during audit / 2 fixtures installed). The average bonus per fixture was \$16.4, which was a result of the interaction between the distribution of low-flow fixtures (shown in Figure 2) and the pattern of retention and disadoption.

We find that, in this context, it would have been better to recruit additional households. It is possible that other patterns of exposure subsidies—e.g. a larger subsidy at a later date—would have outperformed additional recruitment. In particular, holding fixed the size of the exposure subsidy, we suspect that it would have had a greater impact on use at 16 months if it were awarded more than four months after initial installation. The four-month disadoption rate in the no-bonus control group was just 22 percent, so the subsidy only had an opportunity to change behavior among that subset of the population.

Appendix E Tables (for online publication)

Table E.1: Households in sample and water prices by community

Community	Households	Price (Costa Rican Colones)		
		Fixed price per month	First block per m^3	Last block per m^3
Chomes	150	3415	160	195
Los Jocotes	86	2745	150	150
Lepanto	106	3415	160	195
Lomas Matapalo	23	3180	185	225
Moracia	127	2695	155	200
Paso Tempisque	159	3415	160	195
Pueblo Nuevo	50	2800	190	230
San Blas	133	3415	160	195
Santa Rita-Zapal	36	3085	190	230
Total	870			

Note: Households were recruited from nine communities in Guanacaste and Puntarenas provinces in Costa Rica. Households in most communities paid a monthly water bill according to a fixed price per month and schedule of four marginal block prices. Households in Los Jocotes faced a single marginal price of 150 Costa Rican Colones per cubic meter. One Costa Rican Colón was approximately 0.0018 U.S. Dollars at the time of the experiment.

Table E.2: Summary statistics – balance by treatment assignment

Variable	(1) No-bonus control	(2) Bonus treatment	(3) Difference
# of individuals in household	3.81 (1.89)	3.54 (1.66)	-0.27 (0.12)
Owns home	0.85 (0.36)	0.90 (0.30)	0.05 (0.02)
Years in home	17.98 (15.80)	18.50 (14.83)	0.52 (1.04)
Missing income range	0.08 (0.27)	0.07 (0.26)	-0.01 (0.02)
Less than 75,000 CRC/mo	0.12 (0.33)	0.11 (0.31)	-0.02 (0.02)
75,000 to 125,000 CRC/mo	0.20 (0.40)	0.21 (0.40)	0.00 (0.03)
125,000 to 250,000 CRC/mo	0.28 (0.45)	0.30 (0.46)	0.02 (0.03)
250,000 to 450,000 CRC/mo	0.20 (0.40)	0.20 (0.40)	-0.00 (0.03)
More than 450,000 CRC/mo	0.12 (0.32)	0.12 (0.33)	0.01 (0.02)
Imputed income, CRC/mo, thousands	232.05 (162.76)	235.69 (162.11)	3.64 (11.46)
Missing water use	0.03 (0.18)	0.03 (0.18)	-0.00 (0.01)
Cubic meters per month, 2014	24.72 (14.00)	25.44 (15.62)	0.71 (1.02)
Avg monthly water bill, CRC, thousands	7.37 (2.53)	7.47 (2.71)	0.11 (0.18)
Household head completed primary school	0.81 (0.40)	0.81 (0.39)	0.01 (0.03)
Household head completed secondary school	0.29 (0.45)	0.25 (0.43)	-0.04 (0.03)
Fixture locations	2.35 (0.92)	2.42 (0.97)	0.07 (0.06)
Showerhead fixture locations	1.02 (0.26)	1.04 (0.33)	0.02 (0.02)
Bathroom faucet fixture locations	0.76 (0.46)	0.79 (0.46)	0.03 (0.03)
Kitchen faucet fixture locations	0.57 (0.57)	0.60 (0.59)	0.02 (0.04)
Observations	432	438	870

Standard deviations and standard errors in parentheses

Note: This table reports the mean and standard deviation of observable characteristics for households that agreed to participate in the experiment and install water-efficient technology. The baseline survey asked households about income ranges. Imputed income is the average of the lower bound and upper bound of the income range indicated by the household. For the highest income range, imputed income is 125% of the lower bound, 450,000 Costa Rican Colones per month, which is approximately equivalent to \$810 per month, or \$9,720 per year. One Costa Rican Colón was approximately 0.0018 U.S. Dollars at the time of the experiment.

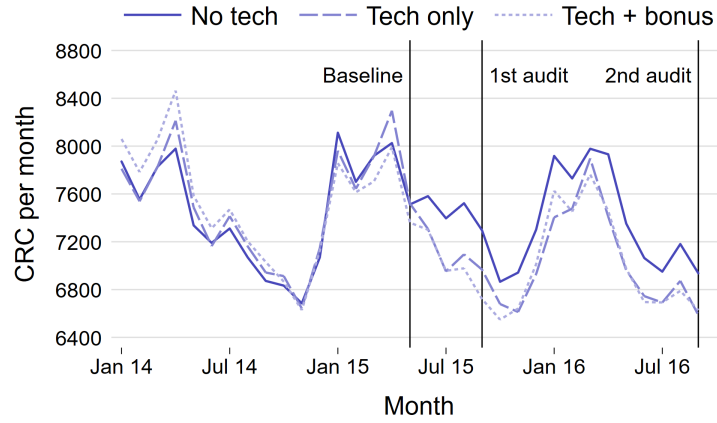
Table E.3: Summary of attrition

Household presence in audits						
	No-bonus control		Bonus treatment		Full sample	
	Count	%	Count	%	Count	%
Treatment assignment	432	100.0	438	100.0	870	100.0
Treatment and outcome data present	341	78.9	383	87.4	724	83.2
Missing treatment	60	13.9	34	7.8	94	10.8
Missing outcome	19	4.4	11	2.5	30	3.4
Missing both	12	2.8	10	2.3	22	2.5
Fixture presence in audits						
	No-bonus control		Bonus treatment		Full sample	
	Count	%	Count	%	Count	%
Treatment assignment	1016	100.0	1060	100.0	2076	100.0
Treatment and outcome data present	829	81.6	937	88.4	1766	85.1
Missing treatment	123	12.1	75	7.1	198	9.5
Missing outcome	42	4.1	26	2.5	68	3.3
Missing both	22	2.2	22	2.1	44	2.1

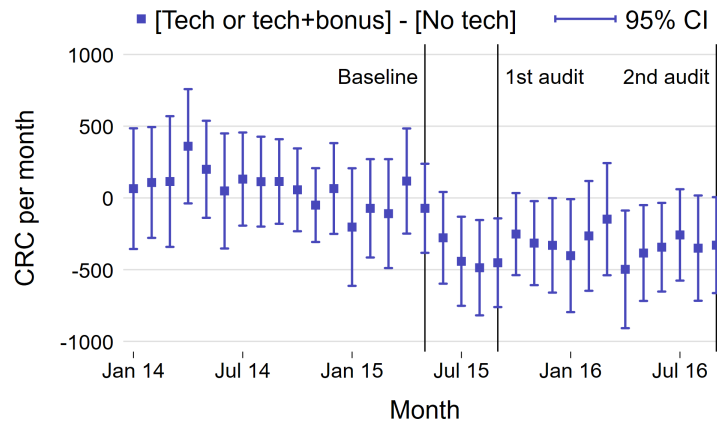
Note: Of the 870 households in the sample, installation was unsuccessful in 6 households, 122 households were missing from the 2015 audit and an additional 30 were missing from the 2016 audit. Fewer households attrited from the bonus treatment group than from the no-bonus control group.

Appendix F Figures (for online publication)

Figure F.1: Average monthly water bill by treatment assignment



(a)



(b)

Note: During a visit by the field team in May–June 2015, households were randomly assigned to one of three treatment conditions: (1) no-technology control (no tech), (2) low-flow water fixtures (tech), or (3) low-flow water fixtures plus a cash bonus if the fixtures were still in use during the first audit (tech+bonus). Households were not told to expect a second audit, and no bonus was promised or paid after the first audit.