Demand response as a common pool resource game: Nudges or peak pricing*

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Abstract

The aim of demand response is to make energy consumption more flexible during peak periods. Using a contextualised common pool resource (CPR) framework, we study energy consumption choices. Subjects choose how much to consume by deciding whether to use five different appliances during 10 periods. The total consumption of these activities is the CPR contribution, and payoffs depend on personal consumption and the amount consumed by the group. In the nudge treatment, subjects are nudged towards the socially optimal level of consumption using injunctive norms. In the price treatment, an increase in price is calculated to incentivise subjects to choose the level of consumption observed in the nudge treatment. The objective is to quantify the nudge via an equivalent price. Across all 10 periods, consumption is significantly lower in treatment groups compared to control groups. We conclude that there are implications for policy makers as the nudge treatment performs as well as an equivalent price without the implied loss of welfare, and that the nudge is understood and integrated into subjects' decision making quicker than an equivalent price.

JEL Classifications: C91, C92, D62, D91, H21

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1 Introduction

In this paper, the main research hypothesis is that the management of end-use consumers in peak periods is similar to the management of agents that use a common pool resource (CPR). Here, the CPR is the limited renewable energy sources which are sustained so long as electricity consumption does not exceed power capacities. Such an approach allows us to explore, in an experimental setting, the impacts of demand response tools on consumers' behaviour when they are placed in the social dilemma resulting from the need to balance supply and demand, while maintaining their desired level of consumption and comfort. Following Ostrom (1990), and more recently Melville et al. (2017) in the energy field, this dilemma is the conflict between the personal interest of consuming electricity without constraint, and the collective interest of maintaining power supply reliability.

This introduction provides background on the impacts of increasing the share of renewable energy on power supply reliability, and consequently on the need for demand response programmes based on monetary, and non-monetary incentives or nudges. The principal objective of the experiment is to use a contextualised CPR game to explore the effect of nudges and peak prices on subjects' consumption choices compared to when no policies are used, and to give a monetary value to the nudge. The secondary objective is to compare subjects' choice of which appliances to use and which electricity-consuming activities to take part in when faced with a need to reduce their demand. The second section of this paper sets out the theory behind the CPR game used in the experiment, and the third section describes the experimental design. The fourth section gives and discusses the results, and the final section concludes and provides policy recommendations.

1.1 Renewable energy and demand response programmes

In the last two decades, we have seen an increase in the share of renewable energy and in distributed power generators (REN21 2016). This phenomenon calls for new strategies in the management of the electricity grid in order to maintain power supply reliability and quality, particularly at times when intermittent energy sources constitute a significant part of total system capacity. This need is all the more important given that the European Union has set ambitious targets to reduce greenhouse emissions and to increase the share of renewable energy sources in the production mix by 2030 (European Commission 2014).

Reliable management of the electricity system requires a perfect balance between supply and demand in real time. Given the increase in renewable energy sources, this balance is harder to achieve as supply and demand levels can change rapidly and unexpectedly, in particular on high demand days when natural conditions are unfavourable for the use of renewable energy sources. Moreover, the power generation infrastructure is highly capital intensive, such that demand side management may be one of the cheaper tools available for balancing supply and demand. Given the greater difficulty of producing peak electricity, there is a need to have a more flexible residential energy demand, particularly during peak periods. Demand response programmes, defined as the changes in electricity usage by end-use consumers from their normal consumption patterns in response to signals, are the main tool used or experimented in the management of the electricity grid (Balijepalli et al. 2011).

Current methods used to incentivise households to lower their energy demand include dynamic tariff structures, informational incentives, or nudge-based incentives. Under certain tariff structures consumers face financial incentives to reduce their energy demand as during certain hours or on days when demand is particularly high, the price of electricity is greater than at off-peak times. This increased price is designed to induce lower electricity use at times with high wholesale market prices or when system reliability is jeopardised (Borenstein et al. 2002; Faruqui et al. 2010a; Faruqui et al. 2010b; Hargreaves et al. 2010; Raw and Ross 2011). Informational incentives involve providing the household with increased information on their consumption to allow them to make a more informed decision. Such incentives include information on how personal consumption compares from one day to another, or on a weekly or a monthly basis (Benders et al. 2006; Houde et al. 2013; Mizobuchi and Takeuchi 2013; Schleich et al. 2013; Carroll et al. 2014; Schultz et al. 2015). Nudge based incentives go beyond simple information by changing the way the information is presented in order to exploit behavioural biases (Schultz et al. 2007; Thaler and Sunstein 2008; Allcott 2011; Ayres et al. 2012).

Our paper is particularly related to laboratory experiments which study the effect of monetary and non-monetary incentives, or nudges, on behaviour. We discuss these areas of literature below.

1.2 Monetary incentives and nudges in the laboratory

In CPR laboratory experiments, monetary incentives are often modelled as taxes. These are found to be a first best policy when it comes to managing behaviours which result in negative externalities (Ballard and Medema 1993). In experimental games with negative externalities, studies have shown that subjects perform at near optimal levels (Plott 1983; Cochard et al. 2005). Yet, taxes are seldom accepted by the public. This can be explained by a preference for the status quo (Cherry et al. 2014), by tax aversion; individuals feel that negative incentives, such as taxes, impede their free-will and are controlling ; by framing; acceptance for taxes increases when the mechanism behind them is explained (Kallbekken et al. 2011; Heres et al. 2013).

Given that monetary interventions such as taxes, and dynamic pricing in the context of electricity consumption , can be politically difficult to implement (Alexander 2010) as well as costly, policy makers have also used non-price interventions to influence households to reduce their energy consumption, such as nudges.

A nudge is defined as a change to a choice setting which alters individuals' behaviour without removing any of the choices available to them nor affecting their economic incentives. Nudges are designed to incentivise individuals to pick an option that is in their best interest, an option which they would not necessarily choose for themselves (Thaler and Sunstein 2008). While the idea of nudges is not recent, the term has certainly seen an increased level of interest in recent years. The nudge intervention used in our experiment relates to both information on suggested play as the feedback is based upon the optimal level of consumption, and on social approval as we add an element of whether an individual's consumption behaviour is approved of or not.

In a CPR game, Delaney and Jacobson (2015) suggest to groups what they should do to increase their payoffs using both informative and normative messaging and compare this to a subsidy. They find that the subsidy is the most effective, followed by normative then informative messaging. The authors note that it is unusual that the normative messaging treatment results in only a slight greater reduction in extraction level when compared to information alone given that previous research has found significant effects on energy and water consumption reduction through the use of normative messages (Schultz et al. 2007; Allcott 2011; Ayres et al. 2012; Ferraro and Price 2013). They suggest that the non-significant difference in the results may be due to small sample sizes (n=15). However, it may also be due to a certain level of overlap between the two treatments, as the information treatment also contains normative language. The two treatments, information and normative messaging should perhaps instead be viewed as a weak normative message and as a strong normative message, respectively.

Boun My and Ouvrard (2017) explore the impact of recommended play, or a nudge, and taxes on contributions to a public good for reducing pollution. They hypothesise that reaction to a nudge is greater when subjects are more sensitive to environmental issues. After measuring environmental sensitivity, subjects are split into groups according to whether they are more or less environmentally sensitive than average and are then faced with either a nudge; a statement of the socially optimal contribution to the public good, or a tax; a linear tax based upon the optimal contribution.

The tax treatment shows the greatest increase in contributions for both high and low sensitivity groups, a 45% and 34% increase in contributions, respectively. They find that the nudge divides subjects according to their environmental sensitivity, with the least sensitive reducing their contribution by 29% compared to the baseline, and the most sensitive increasing their contribution by 14%. In their set-up, Boun My and Ouvrard (2017) create groups of either all highly environmentally sensitive subjects, or of less environmentally sensitive subjects. This is perhaps not entirely reflective of the situations where individuals interact with people of differing levels of environmental sensitivity.

In addition to suggested play, the nature of the nudge used in our experiment provides social approval or disapproval of an individual's behaviour in the game. The rationale is that social approval increases optimal behaviour CPR games as subjects perceive utility (disutility) from social approval (disapproval) Rege and Telle (2004). There is mixed evidence as to whether social information and approval increases or decreases optimal behaviour in collective action games. It has been shown both theoretically (Holländer 1990; Fehr and Schmidt 1999) and experimentally that such social norms can increase contributions in collective action games (Cialdini 2003; Rege and

Telle 2004; Spraggon et al. 2015). In other experiments, social approval has been shown to reduce optimal behaviour (Noussair and Tucker 2007; Brent et al. 2017).

The social approval used in our experiment does not come from the other subjects, but from the regulator who informs subjects via a happy or sad face whether they are consuming more or less than the optimal amount.

2 Theory

Ostrom (1990) defines a common pool resource as a stock of a natural or man-made resource system from which a flow of resource units can be withdrawn. The stock of CPR is renewable and so the stock can be sustained so long as average withdrawal rates do not exceed average replenishment rates. The social dilemma of CPRs is that individuals would like to withdraw more than the sustainable amount resource units from the stock and as such there is a conflict between personal interest and collective interest.

Electricity can be thought of as a CPR; the electricity network (power stations, distribution centres, transmission lines) represents the resource system and the resource units are the kilowatt hours. In the short run, we can consider that this system provides a stock of electricity units available to households. The stock of electricity is renewable in the sense that once electricity has been consumed it must be immediately reproduced in order to maintain supply and demand balance. There is equally a problem of overuse: on days of extreme weather, or when renewable energy resources supply electricity, there is risk of demand outstripping supply which implies a need to reduce the demand of electricity (Bäckman 2011).

2.1 Common pool resource game

A group of n players share a common resource. They each have an endowment e which can be used to invest in the extraction of the common resource. The amount invested in resource extraction by individual i is x_i with Σx_i the amount invested by the group. Extraction of the resource earns each player a for every unit extracted personally, minus b for every unit extracted by the group regardless of who extracts it. The parameter a represents the utility of consuming electricity in terms of increased comfort, the use of appliances without constraint, whereas the parameter b represents the disutility of all subjects' consumption of electricity in terms of voltage reductions and brief power cuts. The cost of investing in the extraction of the resource is c. Each player's profit depends on his own investment in extraction as well as the group investment:

$$\pi_i = e - cx_i + x_i(a - b\Sigma x_i)$$

A rational, self-interested player invests an amount x_i which maximises their profit:

$$max_{x_i}\pi(x_i, \Sigma x_i) = e - cx_i + x_i(a - b\Sigma x_i)$$

The first order condition is:

$$-c + a - bx_i - b\Sigma x_i = 0$$

Supposing that all agents are equal, a symmetric Nash equilibrium can be found such that $x_i = x_j = x$ for all players i, j.

$$x_i = \frac{(a-c)}{b(n+1)}$$

This level of consumption maximises individual profits regardless of the effects of an individual's consumption on the group.

The socially optimal investment in resource extraction is the amount x which maximises the collective profit. Assuming symmetry, the player maximises:

$$max_x n\pi(x) = n[e - cx + x(a - bnx)]$$

The first order condition is:

$$-cn + an - 2bn^2x = 0$$

which gives an optimal investment where:

$$x_i = \frac{(a-c)}{2bn}$$

This level of consumption takes into consideration the effect of each individual's consumption on the network and is equivalent to the level of consumption to be reached when consumers are asked to participate in demand response.

The Nash equilibrium results in a higher level of extraction than the socially optimal amount, hence the social dilemma. One option, to align the private earnings with the social optimum, is to increase the cost of extraction c such that the Nash equilibrium and socially optimum levels of extraction are equal. The cost of extraction c is increased by an amount d and its value is found by equating the Nash equilibrium and the socially optimal solutions. In the context of electricity consumption d is the increase in price during peak periods.

$$\frac{a-c-d}{b(n+1)} = \frac{a-c}{2bn}$$
$$d = \frac{(a-c)(n-1)}{2n}$$

3 Experimental Design

This section details the experimental design beginning with the parametric protocol and the different experimental treatments, followed by the hypotheses to be tested and a description of the participants and the procedure.

3.1 Experimental parameters

The game concerns electricity consumption during 10 peak periods when demand can be greater than production. In the experiment, subjects form groups of four ($n = 4$) for 10 peak periods ($t = 10$). Subjects remain in the same groups for the duration of the experiment. Each group makes up an electricity consumption system of four households which represent a neighbourhood or small society. In this context the demand response challenge is represented as a repeated CPR game.

At the start of each period, each subject receives an endowment $e = 100$ ECU[1] which they can use to consume electricity (measured in energy units (EU)). In the control and nudge treatments each EU costs 1 ECU ($c = 1$). The cost of each EU changes in the price treatment ($c = 3$) as discussed below. Any ECU that the subject does not use to consume electricity is kept by the subject and included in their profit function. For every EU consumed, the subject receives $a = 13$ and every EU consumed costs $b = 0.1$ for all subjects in the group regardless of who consumed it. Subjects' profit function is as follows :

$$\pi_i = 100 - cx_i + x_i(13 - 0.1\Sigma x_i)$$

Individually, subjects maximise their profit at the Nash equilibrium, $x^{NE} = 24$ for an individual profit of 158 ECU. This level of consumption is greater, and the payoff is lower than if subjects maximised the collective gains. Collectively subjects should each consume $x^{SO} = 15$ for an individual profit of 190 ECU. This represents the collective interest in lowering consumption for demand response.

In each period, subjects must decide how much of their endowment to spend on consuming electricity by choosing whether or not to use five different electrical items. Table 1 details the different levels of consumption that subjects can choose from. Subjects are told that their electricity consumption brings them comfort (via a monetary gain) of 13 ECU for every unit consumed and that the total consumption of their group leads to a reduction in personal comfort due to voltage reductions and brief power cuts when demand is greater than supply (a monetary cost). The greater the total consumption of the group, the greater the reduction in comfort.

When deciding whether or not to use the different electrical appliances proposed, subjects are choosing to consume energy units in increments of 5. We discretise the choice of electricity consumption to reflect the idea that in real life individuals consume

[1] ECU = Experimental Currency Units. The exchange rate is communicated to all subjects during the instruction phase and is 150 ECU = 1€.

Item	Consumption levels	Consumption amount (EU)
Electric heating	Unchanged	15
	1°C reduction in heating	10
	2°C reduction in heating	5
Electric water heater	On	5
	Off	0
Washing machine/ dishwasher	On	10
	Off	0
Cooking equipment	On	10
	Off	0
Television/ Computer	On	5
	Of	0

Table 1: Electricity consumption choices

electricity by turning appliances on or off. We allow three levels of consumption for the heating choice. Given the discretisation of the consumption amount, the Nash equilibrium is $x_i = 25$ EU and the social optimum is $x_i = 15$ EU. To assist subjects in deciding how many EU to consume, a simulator[2] is available as well as a printed profit table. At the end of each period, subjects see how much they have consumed and their profit for the period.

3.1.1 Nudge treatment

In the nudge treatment, in addition to the above, subjects are told that one way to avoid power cuts is to ask consumers to lower their consumption during peak periods. This implies a lower level of comfort (as the individual may lower their heating or use their washing machine at a different time, for example) but allows all individuals, including oneself, to avoid a much lower comfort level, i.e. a power cut, or a reduction in the quality of electricity distribution.

At the end of each period, subjects receive additional feedback on their consumption. If their choice of consumption is less than or equal to the level of consumption which minimises the reduction in comfort for the group, i.e.: the socially optimal level, they see a picture of a smiley face. If their consumption is greater than this level, then they see a sad face.

3.1.2 Price treatment

In the price treatment, subjects are told that voltage reductions and brief power cuts can be avoided by incentivising consumers to consume less during peak periods by

[2]The simulator is described to subjects during the explanation of the game phase. Slides of the presentation of the game are available in French by request to the corresponding author.

increasing the price of electricity. The price for this treatment is calculated with respect to the average levels of consumption observed in the nudge treatment. Subjects are told that each energy unit consumed during the peak period costs 3 ECU which is three times more expensive than in a normal period[3]. The goal is to compare whether the price results in the same level of consumption as the nudge when the price implemented is designed to achieve the level of consumption observed in the nudge treatment. The average level of consumption observed in the nudge treatment is 19.07 across all periods. Given that subjects can only choose consumption in increments of 5, the price is calculated such that the Nash equilibrium consumption level in the price treatment is $x_i^{NE,P} = 20$.

$$\begin{aligned}\frac{a-c-d}{b(n+1)} &= 20\\ \frac{13-1-d}{0.1(4+1)} &= 20\\ d &= 2\end{aligned}$$

The price increase required to incentivise subjects to consume 20 EU is equal to 2. The price of electricity for subjects in the price treatment is thus equal to 3 ECU.

In this treatment the subjects maximise:

$$max_{x_i}\pi(x_i, \Sigma x_i) = 100 - 3x_i + x_i(13 - 0.1\Sigma x_i)$$

The feedback given at the end of each period is the subject's level of consumption and their earnings for that period.

3.2 Hypotheses

Under the assumption that subjects are rational and self-interested, we would expect them to choose the Nash equilibrium consumption amount in all treatments, i.e.: 25 in the control and nudge treatment, and 20 in the price treatment. Such players would not be influenced by the nudge described above.

Previous experiments have shown that suggesting a course of action has a positive influence on socially optimal behaviour (Dal Bó and Dal Bó 2014; Delaney and Jacobson 2015; Boun My and Ouvrard 2017). Other experiments have found that aligning the Nash equilibrium with the social optimum via the use of a tax (framed as a price increase in our experiment) is a first best policy for dealing with social dilemmas in public good and CPR games (Plott 1983; Ballard and Medema 1993; Cochard et al. 2005). However, such interventions are not always well-received by the public. In the context of electricity consumption, varying price structures or dynamic pricing also has its opponents (Alexander 2010). This leads to our main hypotheses:

[3]This is comparable to tariffs proposed by EDF at the time of the experiment; the highest peak price is approximately 3.5 times the standard tariff (EDF 2016).

Hypothesis 1 *Consumption choices in the nudge treatment will be lower than in the control treatment.*

Hypothesis 2 *Consumption choices in the price treatment will be lower than in the control treatment.*

Hypothesis 3 *When the price level is fixed according to the nudge result, consumption choices in the price treatment will be equivalent to those in the nudge treatment.*

Furthermore, the positive impact of suggested play or a nudge is increased when an element of social approval or disapproval is included (Dal Bó and Dal Bó 2014), as such we expect the following:

Hypothesis 4 *Subjects who receive 'happy face' feedback will not change their consumption in the following period (those who consume the optimal amount or less).*

Hypothesis 5 *Subjects who receive 'sad face' feedback will lower their consumption in the following period (those who consume more than the optimal amount).*

Due to the nature of the CPR game, we consider that altruism may also influence a subject's choice of consumption. Furthermore, it has been shown in a previous experiment (Boun My and Ouvrard 2017) that subjects' reaction to a nudge in an environmental setting depends on their environmental sensitivity. This leads us to formulate the following hypotheses:

Hypothesis 6 *More environmentally sensitive and altruistic subjects will consume less than less environmentally sensitive and altruistic subjects in all treatments.*

Hypothesis 7 *More environmentally sensitive subjects will consume less in the nudge treatment than in the price treatment.*

3.3 Participants and Procedure

240 subjects took part in the experiment, during 12 sessions[4] in March and April 2017 at Grenoble Applied Economics Laboratory (GAEL). Each session lasted one and a half hours. At the beginning of each session, subjects randomly chose a subject number and a computer post. Once the subjects were seated, the experimenter read aloud all instructions. These were also displayed on two screens at the front of the room which all subjects could see. After general instructions concerning confidentiality, anonymity of data and the code of conduct are given, the experimenter described the context of the game.

Table 2 shows the number of subjects, groups, and sessions per treatment. The experiment was programmed using zTree software (Fischbacher 2007). For participating

[4]During the 8th session a technical problem occurred and so the results of this session are excluded from the analysis. The excluded session would have been in the price treatment.

in the experiment, subjects received a 10€show-up fee. In addition, subjects earned 7€20 to 18€00, with average earnings across sessions of 12€30. The majority of subjects were undergraduate students in various disciplines (67%), 59% were female subjects, and the average age across subjects was 22 years.

Treatment	Number of subjects	Number of groups	Number of sessions
Nudge	100	25	5
Price	80	20	4
Control	60	15	3
Total	240	60	12

Table 2: Number of subjects per treatment

Each session began with instructions being read aloud by the experimenter and displayed on two screens at the front of the room. Subjects were told that the experiment would include several phases. The first phase of the experiment was the CPR game. The second phase involved a risk aversion test (Holt and Laury 2002). In the third and final phase, subjects completed three questionnaires: the General Ecological Behaviour Scale (Kaiser 1998)[5], an altruism questionnaire (Costa and McCrae 1992) and finally a demographic questionnaire. We included a questionnaire on altruism as the nature of the game requires making a decision that affects other people, and so we wish to control for altruistic tendencies in our analysis. We also measure risk attitudes[6].

The instructions for each phase were read aloud then the subjects completed the phase before listening to the instructions on the following phase. Before the beginning of the CPR game phase, subjects completed a questionnaire to determine their understanding of the game. Subjects were informed of any wrong answers and had to correct them before advancing to the first period of the game.

4 Results and discussion

In this section, we describe and discuss the results, beginning with descriptive statistics and a graphical analysis of group level consumption decisions, followed by non-parametric testing and regression analysis. Next the individual choices of subjects are analysed, for all treatments and specifically for the nudge treatment according to the message received. We also consider the effect of treatment on subjects' welfare. We then describe the results of questionnaires used at the end of the experiment and the consumption decisions by type as identified by the questionnaires. Finally, we consider the equipment choices made by subjects.

[5]Following Boun My and Ouvrard (2017), we use a shorter version of the GEB scale including 28 items. See Appendix A and Appendix B for details of the GEB and altruism questionnaires.

[6]Analyses on risk attitudes were not conclusive and so are not discussed further in the rest of the paper.

4.1 Average consumption at the group level

The dynamics of average group consumption by treatment for each period is represented in fig. 1. Table 3 summarises the average group consumption by treatment overall and in periods 1 and 2, as this is pre and post initial feedback. To further analyse the results, we also perform non-parametric tests on average group level consumption between and within treatments compared to the corresponding Nash equilibrium and to the social optimum. The second part of table 3 gives these results.

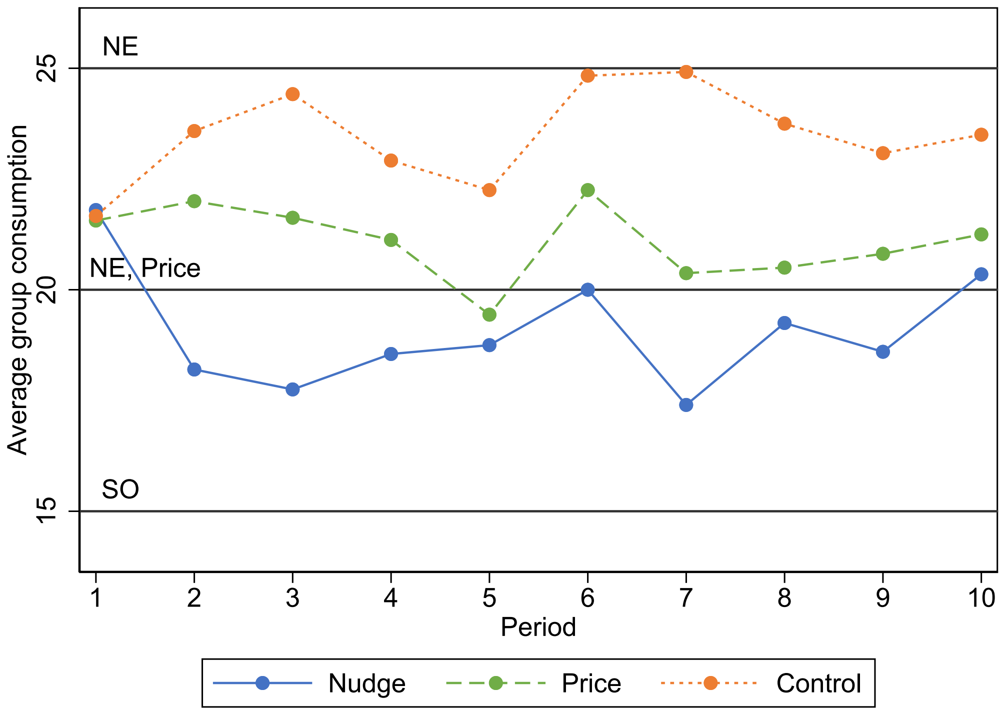

Figure 1: Dynamics of average consumption by treatment

In the absence of any policies, the control groups consume 23.49 on average. Though this level of consumption is close to the Nash equilibrium level of our initial game, it is significantly different from 25 EU (p-value = 0.0355, Wilcoxon signed-rank test). When average consumption per period is tested, average consumption in the control group is not significantly different from the NE in all but 3 periods. In periods 1, 5 and 9, average consumption is at its lowest and significantly different from 25 for the control groups (p-values $<$0.05, Wilcoxon signed-rank test). This first result shows that in the absence of policy, subjects do not achieve the socially optimal level of consumption.

In the nudge treatment, we see that post-feedback, consumption is consistently lower compared to the control groups (p$<$0.01, Wilcoxon rank-sum test), thus supporting hypothesis 1. The use of a nudge results in the lowest level of consumption of 19.07 on average across all 10 periods. This is to be expected given that the objective of the

Treatment	Period 1	Period 2	Overall
Nudge	21.80	18.20	19.07
	(4.43)	(3.08)	(4.45)
Price	21.56	22.00	21.09
	(3.71)	(3.17)	(3.66)
Control	21.67	23.58	23.49
	(3.67)	(4.11)	(4.18)
Wilcoxon rank-sum test (Between treatment p-values)			
Nudge = Price	0.9083	0.0004	0.0046
Nudge = Control	0.9216	0.0005	0.0001
Price = Control	0.9194	0.2027	0.0035
Wilcoxon signed-rank test (Within treatment p-values)			
Nudge = Social optimum (15 EU)			0.0000
Nudge = Nash equilibrium (25 EU)			0.0000
Control = Social optimum (15 EU)			0.0007
Control = Nash equilibrium (25 EU)			0.0355
Price = Nash equilibrium (20 EU)			0.0057

Standard deviations in brackets

Between treatment p-values are p-values of Wilcoxon rank-sum tests.

Within treatment p-values are p-values of Wilcoxon signed rank tests.

Table 3: Mean group consumption by treatment

nudge is to encourage subjects to consume the optimal level of consumption of 15. In the first period, all treatments start at a similar level of average consumption[7]. Given that in the nudge treatment, subjects do not receive feedback until after having made their consumption decision, it is to be expected that average group consumption in the first period will be similar between the nudge and control groups. We see in fig. 1. that after the initial feedback, the average consumption immediately decreases and from period 2, there is a significant and permanent effect of the nudge policy as the average level of consumption under the nudge treatment is significantly different to those of control groups.

In the price treatment, when the price is increased such that consumers are incentivised to consume 20, (i.e. the corresponding level of the nudge treatment), the average group level of consumption is 21.09. This observed level of consumption is lower than that of control groups thus providing evidence to support hypothesis 2. In this treatment, subjects are aware of the price change prior to any decision making. We would therefore expect there to be a significant difference between consumption decisions in the price treatment compared to control groups in the first period, but this difference is not significant (p-value = 0.9194). The average group consumption is only consistently and significantly different from the seventh period. It is also significantly different in periods 3 and 5 (p-value$<$0.05, Wilcoxon rank-sum test). This suggests that it takes several periods for the subjects to integrate the price increase into their decision making and that it is not until the seventh period that the price is fully integrated into their decision making process.

Given that the price increase is designed to incentivise subjects to consume the amount observed under the nudge treatment, we do not expect to see significant differences between the average group consumption decisions from the second period onwards between the nudge and price treatments. However, we see significantly different levels of consumption in periods 2 and 3 (p$<$0.01, Wilcoxon rank-sum test). This suggests that subjects do not immediately integrate the price increase into their decision making. They require a few periods of play before they take into consideration the effect of the price increase on their consumption level. This result provides partial support for hypothesis 3, as consumption under the price increase is greater initially, and consumption choices in the two treatments are at similar levels from period 4.

Finally, for all 10 periods, consumption across the three treatments is significantly different (Kruskal-Wallis test, p=0.0001). In both the nudge treatment and the control groups, the observed average levels of consumption are significantly different from both the Nash equilibrium of 25 and the social optimum of 15 (p$<$0.05). Groups in the nudge and price treatments have an average level of consumption that is significantly different from the control groups (p$<$0.01). Moreover, the average consumption observed in the nudge treatment is significantly different from that observed in the price treatment (p$<$0.01).

[7]This difference is insignificant as tested non-parametrically using the Kruskal-Wallis test (p=0.9899).

The results described in this section are robust to panel data estimation as shown in table 4 which presents regression estimates of treatment effects. The models have been estimated using panel data random effects estimation. Panel data methods are used as there are n subjects making a consumption decision in t periods. Random effects estimation is preferable to OLS or fixed effects estimation as it is more efficient than fixed effects estimation, and given that we have used a between-subject design, random effects estimation allows us to model the time-invariant treatment variables (Moffatt 2015).

The value of the constant represents the average group contribution controlling for different variables. All specifications show a clear significant effect of both the nudge and price treatments compared to the control groups. In models 2 and 4, a period variable is included to control for variation during the game, however, the coefficient is not significant. In models 3 and 4, dummy variables are added to specify whether the group under or over consumed compared to the optimal consumption in their treatment[8]. At the group level, there is no significant effect on consumption due to under- or over-consuming in the previous period. Given that feedback on under or over consumption is provided at the individual level and in the nudge treatment, this effect is explored in more detail in the following section.

4.2 Average consumption at the individual level

Table 5 shows the regression estimates of random effects models of treatment and covariates on individual consumption choice. Model 1 shows a significant treatment effect for both the nudge and the price treatment at the individual level. In even numbered models, profit in *t-1* is included and has a significant but small positive effect on average individual consumption. As the amount earned in *t-1* increases, subjects increase their consumption in t. This could be indicative of a rebound effect where subjects who earn more, increase their consumption.

Models 3, 4 and 7 show that individuals who under-consumed in *t-1*, reduce their consumption in t compared to optimally consuming individuals. Those who over-consume in *t-1* continue to do so compared to optimally consuming individuals. Once individual consumption type is controlled for, the significant effect of the price treatment falls out as the price treats all individuals equally and does not differentiate according to how an individual consumes (under, optimally, or over).

Finally, in models 5-7, we include variables concerning subjects' sensitivity towards the environment and their level of altruism[9]. Individuals who are more sensitive to environmental issues consume less. Given the context of the CPR game as an electricity consumption decision, such individuals may have additional motivation to choose a lower level of consumption so as to decrease their hypothetical impact on the environment. There is no significant effect of altruism on consumption choice.

[8]The share of each type of group (under, optimal or over-consuming) is shown in table 12 in Appendix C

[9]The construction of these variables is explained in section 4.4

	(1)	(2)	(3)	(4)
Nudge	-4.427***	-4.427***	-4.740***	-4.731***
	(0.830)	(0.830)	(0.807)	(0.808)
Price	-2.398***	-2.398***	-2.272**	-2.254**
	(0.702)	(0.703)	(0.716)	(0.718)
Period		-0.018		0.058
		(0.052)		(0.055)
Group under consumed (t-1)			-0.757	-0.744
			(0.683)	(0.681)
Group over consumed (t-1)			0.288	0.340
			(0.590)	(0.609)
Constant	23.492***	23.588***	23.415***	23.015***
	(0.607)	(0.670)	(0.795)	(0.935)
Observations	600	600	540	540

Standard errors in parentheses

Robust standard errors clustered by group

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4: Average group consumption (random effects estimation)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Nudge	-4.427***	-5.655***	-3.899***	-4.802***	-4.275***	-5.515***	-3.794***
	(0.829)	(0.952)	(0.720)	(0.840)	(0.835)	(0.955)	(0.720)
Price	-2.398***	-1.799*	-0.843	-0.062	-2.318**	-1.742	-0.802
	(0.701)	(0.901)	(0.636)	(0.872)	(0.759)	(0.943)	(0.677)
Profit in t-1		0.033***		0.037***		0.032***	
		(0.005)		(0.007)		(0.005)	
Individual under consumed (t-1)			-2.091***	-1.619**			-2.013***
			(0.584)	(0.572)			(0.575)
Individual over consumed (t-1)			3.589***	3.342***			3.572***
			(0.496)	(0.483)			(0.497)
High Environmental sensitivity					-1.545*	-1.447*	-1.314*
					(0.655)	(0.669)	(0.552)
High Altruism					-0.856	-0.603	-0.492
					(0.652)	(0.651)	(0.527)
Constant	23.492***	18.682***	21.294***	15.785***	24.732***	19.807***	22.229***
	(0.606)	(1.189)	(0.672)	(1.494)	(0.800)	(1.366)	(0.851)
Observations	2400	2160	2160	2160	2400	2160	2160

Standard errors in parentheses

Robust standard errors clustered by group

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5: Average individual consumption (random effects estimation)

We also examine the effect of the nudge on individual consumption decisions. The estimates are shown in table 6. Subjects who under consume receive a smiley face message and subjects who over consume receive a sad face message. Compared to optimally consuming groups, these messages have the effect of reinforcing an individual's behaviour in the previous period. With regard to the feedback received by subjects in the nudge treatment, we find that both hypotheses 4 and 5 are rejected, as rather than nudging subjects towards the socially optimal level of consumption, the nudge employed in this experiment reinforces subjects' existing behaviour. Subjects who under (over) consume in the previous period tend to decrease (increase) their consumption in the present period. The magnitude of the change in consumption is greater for those who over consumed previously. This suggests that while the nudge shows a decrease in average consumption at the group level, at the individual level the nudge may serve to reinforce behaviours that are already present.

At the individual level in the nudge treatment, environmental sensitivity and level of altruism have a significant effect on consumption choice. More environmentally sensitive and altruistic individuals consume less compared to less environmentally sensitive and altruistic individuals.

	(1)	(2)
Under consumption :-) (t-1)	-2.317**	-2.241**
	(0.791)	(0.792)
Over consumption :-((t-1)	4.067***	3.753***
	(0.765)	(0.846)
High Environmental sensitivity		-2.453***
		(0.673)
High Altruism		-1.732*
		(0.846)
Constant	17.203***	19.770***
	(0.408)	(1.021)
Observations	900	900

Standard errors in parentheses

Robust standard errors clustered by group

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 6: Effect of message on individual consumption in nudge treatment

4.3 Welfare analysis

In this section we analyse the effect of the different treatments on subjects' welfare, at both the group and the individual level. Table 7 compares the average observed welfare by treatment at the group and individual level.

We can see that both individually and at the group level, subjects are worst off in price treatment, and better off in the nudge treatment. The increase in the peak price of electricity consumption results in a loss of welfare for individual subjects, or households, and for the group of subjects, or neighbourhood or society. Given that in the nudge treatment, there is no change in price, subjects' welfare is not affected. As such subjects are nudged towards the optimum and so their welfare, both individually and at the group level, is greater than for control groups.

Treatment	Average observed welfare	Welfare at social optimum	Welfare at Nash equilibrium	Welfare at a consumption of 20
		Group level		
Nudge	702	760	600	720
Price	510	-	-	560
Control	617	760	600	720
		Individual level		
Nudge	175	190	150	180
Price	128	-	-	140
Control	154	190	150	180

We do not provide a welfare level for the price treatment for the socially optimal and Nash equilibrium levels of consumption as the price is designed such that the Nash equilibrium level of consumption is equal to 20 as observed in the nudge treatment. We provide the welfare associated with this level of consumption in the final column.

Table 7: Welfare analysis at the group and the individual level

4.4 Questionnaire results

In this section we detail the results of the questionnaires completed after the CPR game regarding environmental sensitivity and altruism.

4.4.1 General Ecological Behaviour Scale

The GEB questionnaire measures an individual's environmental sensitivity Kaiser (1998). In their public good experiment, Boun My and Ouvrard (2017) find that subjects react to a nudge depending on their level of environmental sensitivity. Of the

28 items in the questionnaire, the mean score per item is 3.34 (std. dev. = 0.22). Cronbach's $\alpha = 0.73$[10]. The GEB scale is therefore acceptable.

The average environmental sensitivity level of subjects overall, and per treatment is presented in table 8a, followed by the between treatments tests in table 8b. The average level of environmental sensitivity appears to be similar between treatments. The p-values presented in table 8b tell us that the levels are statistically different from one another between the nudge and the price treatments, and the nudge and control groups.

Nudge	Price	Control	Overall
108.8	106.5	107.1	107.6
(10.25)	(10.64)	(9.61)	(10.00)

Standard deviations are in brackets.

(a) Average environmental sensitivity

	Price	Control
Nudge	0.0001	0.0000
Price		0.7534

(b) Between treatment p-values

Table 8: Generalised Ecological Behaviour Scale

Table 9a shows the average consumption decisions of individuals in each treatment according to their sensitivity to environmental issues. High environmental sensitivity is classed as greater than the average of the sample[11]. As can be seen from the table, overall and for each treatment, more environmentally sensitive subjects choose to consume less. The difference in consumption level by environmental sensitivity is the greatest in the nudge treatment. This difference is statistically significant as shown in table 9b.

Treatment	Low	High	Total
Nudge	20.68	17.90	19.07
Price	21.38	20.86	21.09
Control	24.14	22.88	23.49
Total	21.85	20.04	

(a) Average individual consumption

		High		
		Nudge	Price	Control
Low	Nudge	0.0000		
	Price		0.2036	
	Control			0.1770

(b) Between treatment p-values

Table 9: Average individual consumption by treatment and by environmental sensitivity

In line with Boun My and Ouvrard (2017), we find that subjects' response to the nudge depends on their level of environmental sensitivity. When comparing behaviour under each treatment by level of environmental sensitivity we see that in the nudge treatment, subjects consume less than in the price treatment. This difference is greater

[10] Boun My and Ouvrard (2017) found a Cronbach's $\alpha = 0.74$.

[11] In the nudge, price and control groups, 58%, 55% and 52% of subjects have high environmentally sensitivity, respectively.

for more environmentally sensitive subjects. These results provide support for hypotheses 6 and 7.

4.4.2 Altruism Questionnaire

The altruism questionnaire is used to measure how altruistic subjects are. The mean score per item is 3.28 (std. dev. = 0.33). Cronbach's α is 0.68. The altruism questionnaire is moderately acceptable.

The average altruism scores are reported in table 10a across all subjects and by treatment and the associated p-values in table 10b. The average scores on the altruism tests are significantly different across the nudge and price, and the nudge and control treatments. They are not significantly different between the price and control treatments.

Nudge	Price	Control	Overall
32.89	31.76	32.35	32.38
(4.35)	(4.56)	(3.44)	(4.24)

(a) Average individual altruism score

	Price	Control
Nudge	0.0000	0.0000
Price		0.5779

(b) Between treatment p-values

Table 10: Altruism questionnaire results

Table 11a shows the individual consumption decisions by treatment according to each subject's level of altruism and table 11b the associated non-parametric tests. High altruism is greater than the average of the sample[12]. In the nudge treatment highly altruistic individuals choose to consume less than less altruistic individuals. The levels are similar across altruism types in the control groups, and the opposite is observed in the price treatment. With regard to statistical significance, the differences are only significant in the nudge treatment. As with environmental sensitivity, it appears that a nudge based policy can separate subjects based upon their level of altruism, thus providing further support for hypothesis 6.

4.5 Equipment choices

This section looks at the hypothetical choices of subjects with regard to which electricity consuming activities they are willing to shift during peak periods. The consumption choices available to subjects are presented above in table 1. Figure 2 shows the share of subjects willing to lower the temperature of their heating by treatment type across periods. Figure 3 shows the percentage of subjects choosing to turn on each of the other appliances, by treatment, in each period.

[12] In the nudge, price and control groups, 58%, 55% and 52% showed a high altruism level, respectively.

Treatment	Low	High	Total
Nudge	20.57	17.97	19.07
Price	20.88	21.27	21.09
Control	23.66	23.34	23.49
Total	21.51	20.32	

(a) Average consumption by altruism leveL

		High		
		Nudge	Price	Control
Low	Nudge	0.0000		
	Price		0.6936	
	Control			0.6117

(b) Between treatment p-values

Table 11: Average individual consumption

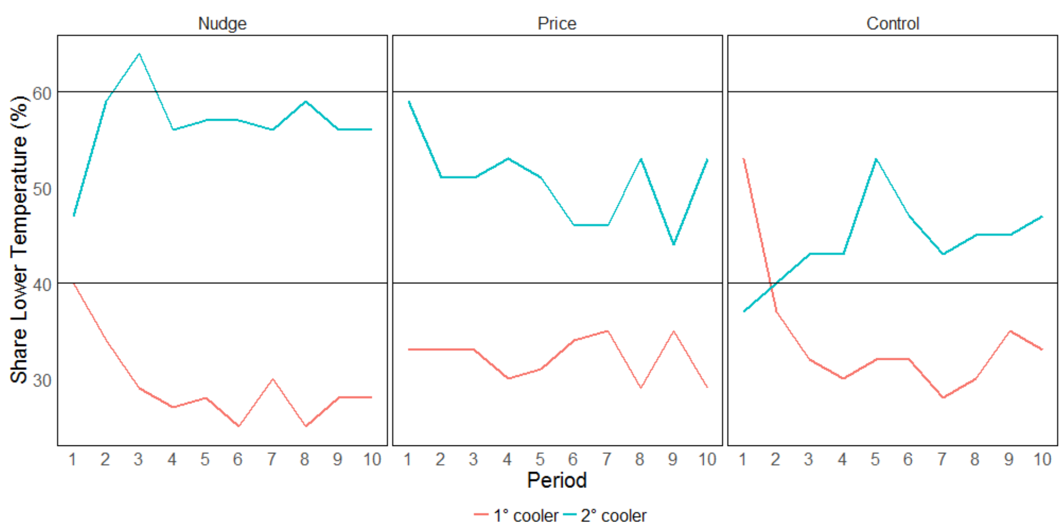

Figure 2: Dynamics of heating usage by treatment

In fig. 2 we can see that the majority of subjects are willing to lower their heating by 2°. In the nudge treatment, after feedback has been received, there is an increase in the number of subjects choosing to lower their consumption by 2°from 47% to 59%, and a decrease in those lowering the temperature by 1°. The same can be observed for control groups but to a lesser extent. Of the subjects who choose to keep their heating at the same temperature, a greater percentage are present in the control groups and fewer in the nudge treatment.

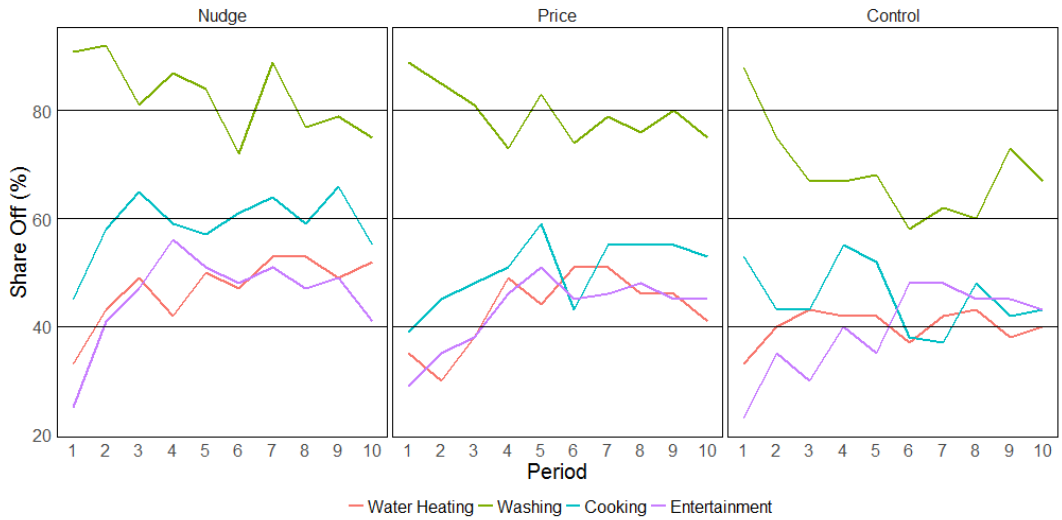

Figure 3: Dynamics of appliance usage by treatment

In fig. 3, across all treatments, we see that subjects are most willing to shift their use of washing machines or dishwashers. Across the 10 periods of the game, just under 80% of subjects choose to turn off these machines across treatments. This share is slightly higher for the nudge and price treatment compared to control groups. There appears to be a small effect of treatment on washing equipment use, as in the control groups we can see a large decrease in the share of subjects who decide to shift their use of such equipment during the course of the game, compared to the treatment groups.

Figure 3 shows electricity consuming entertainment activities to be the activity that subjects are least willing to shift, at least initially with three-quarters of subjects choosing to turn on their televisions and computers in the first period, across all treatments. However, as the game progresses this appliance choice sees an increase in the share of subjects shifting its use.

The share of subjects willing to shift their use of cooking equipment is greater in the nudge treatment than in the price treatment and control groups, and remains around the 60% mark post initial feedback.

Concerning subjects use of water heating, there is an increase in the share of subjects turn off their water heater in the nudge and price treatments. Whereas, the share remains lower in the control groups.

Across treatments, the shift in use of appliances is most apparent in the nudge treatment. With a marked increase in the share of subjects turning off appliances post feedback in period 2. This trend is also visible to a certain extent in the price treatment, and much less so in the control groups.

5 Conclusion and policy implications

The experiment described in this paper explored subjects' responses to a nudge and a peak price based intervention on a contextualised CPR game. The experimental design allowed for a comparison of behaviour under a nudge policy and an equivalent price increase to an absence of policies. The nudge policy experimented was feedback on an individual's consumption choice in the form of a smiley face if they consume the socially optimal amount or less, and a sad face if they consume more than the socially optimal amount. In addition, the experimental design provided an opportunity to examine subjects' consumption choices regarding their use of different appliances as subjects were asked to decide whether to use or not five different appliances when deciding upon their level of consumption. The results of the experiment may be of interest to policy makers when considering the implementation of a nudge or a price based intervention designed to reduce households' energy consumption during peak periods.

In the absence of energy conservation policies, individuals do not achieve the socially optimal level of consumption. When a policy is introduced, a nudge or price increase, individuals significantly reduce their consumption and the latter remains lower than that of individuals who do not experience any policy measures. Both the nudge and price increase result in a level of consumption that is halfway towards the optimal level compared to no policies. However, the nudge does so without the loss of both individual and group welfare that is associated with the price increase. Therefore, while both the nudge and price increase lead to a lower level of comfort due to the reduction in consumption, we conclude that although the nudge in itself is not sufficient to achieve the social optimum, it performs as well as an equivalent price increase without the implied loss of welfare.

The experiment showed that the nudge was quickly and easily understood, and resulted in an immediate reduction in consumption in the period following initial feedback. On the other hand, individuals took longer to understand the effect of the increased price on their consumption and so took longer to integrate it into their decision making process.

The advantage of a nudge policy is that, at the group level, it results in an immediate and significant reduction in consumption, however caution must be taken as a nudge in terms of social norms reinforces the existing behaviour of individuals and divides the population into those who under or over consume, or who are more or less environmentally sensitive or altruistic.

In response to a smiley face, individuals who under consumed previously tended to further decrease their consumption compared to optimally consuming individuals. Whereas, those who received a sad face tended to increase their consumption. Collectively, these individuals compensate for one another's behaviour and so the nudge has an effect on average consumption. However, individually the nudge appears to encourage those who already under consume to consume less, and those who over consume to consume more. In practice, this could lead to a situation where low-consuming households are further reducing their consumption to compensate for the increasing consumption of high-consuming households. While we have obtained this result in a hypothetical consumption game, it is worth consideration when implementing such nudges in the field.

In addition to reinforcing existing consumption behaviour, the nudge had a greater conservation effect on individuals who are environmentally sensitive and show altruistic traits. Such individuals consumed less than their less environmentally sensitive and less altruistic counterparts. The price increase showed no such effect. It would appear that the increase in price crowds out any existing motivation to reduce consumption due to environmental or altruistic tendencies.

Finally, we also consider which appliances subjects are willing to not use in order to reduce their consumption. We find that subjects are most willing to turn off their washing appliances and prefer to continue to use their entertainment devices. Subjects are also willing to lower their heating in order to reduce their total consumption. This also shows the need for further research into specialised nudges according to the types of electric appliances in each household.

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A General Ecological Scale Questions (Kaiser 1998)

1. I use energy-efficient bulbs.
2. If I am offered a plastic bag in a store, I take it.
3. I kill insects with a chemical insecticide.
4. I collect and recycle used paper.
5. When I do outdoor sports/activities, I stay within the allowed areas.
6. I wait until I have a full load before doing my laundry.
7. I use a cleaner made especially for bathrooms, rather than an all-purpose cleaner.
8. I wash dirty clothes without pre-washing.
9. I reuse my shopping bags.
10. I use rechargeable batteries.
11. In the winter, I keep the heat on so that I do not have to wear a sweater.
12. I buy beverages in cans.
13. I bring empty bottles to a recycling bin.
14. In the winter, I leave the windows open for long periods of time to let in fresh air.
15. For longer journeys (more than 6h), I take a plane.
16. The heater in my house is shut off late at night.
17. I buy products in refillable packages.
18. In winter, I turn down the heat when I leave my house for more than 4 hours.
19. In nearby areas, I use public transportation, ride a bike, or walk.
20. I buy clothing made from all-natural fabrics (e.g. silk, cotton, wool, or linen).
21. I prefer to shower rather than to take a bath.
22. I ride a bicycle, take public transportation, or walk to work or other.
23. I let water run until it is at the right temperature.
24. I put dead batteries in the garbage.
25. I turn the light off when I leave a room.

26. I leave the water on while brushing my teeth.
27. I turn off my computer when I'm not using it.
28. I shower/bathe more than once a day.

B Altruism Questions (Costa and McCrae 1992)

1. Some people think that I am selfish and egotistical.
2. I try to be courteous to everyone I meet.
3. Some people think of me as cold and calculating.
4. I generally try to be thoughtful and considerate.
5. I'm not known for my generosity.
6. Most people I know like me.
7. I think of myself as a charitable person.
8. I go out of my way to help others if I can.

C Group type (under, optimal or over-consuming)

Table 12: Number of groups by consumption level (across all periods)

		Group consumption			
		Under	Optimal	Over	Total
	Nudge	42	17	191	250
		16.8%	6.8%	76.4%	100.0%
Treatment	Price	66	26	108	200
		33.0%	13.0%	54.0%	100.0%
	Control	0	4	146	150
		0.0%	2.7%	97.3%	100.0%
	Total	108	47	445	600
		18.0%	7.8%	74.2%	100.0%

For the nudge and control groups, the optimal consumption level is 60. In the price treatment, it is 80.

D Individual type (under, optimal or over-consuming)

Table 13: Number of groups by consumption level (across all periods)

		Individual consumption			
		Under	Optimal	Over	Total
	Nudge	190	316	494	1,000
		19.0%	31.6%	49.4%	100.0%
Treatment	Price	234	295	271	800
		29.3%	36.9%	33.9%	100.0%
	Control	75	79	446	600
		12.5%	13.2%	74.3%	100.0%
	Total	499	690	1,211	2,400
		20.8%	28.7%	50.5%	100.0%

For the nudge and control groups, the optimal consumption level is 15. In the price treatment, it is 20.

E Distribution of messages received in nudge treatment

Table 14: Distribution of messages received in nudge treatment by period

Message received (t-1)	Period 2	3	4	5	6	7	8	9	10	Total
Under consumption :-) (t-1)	9	18	22	19	18	20	24	20	24	174
	5.2%	10.3%	12.6%	10.9%	10.3%	11.5%	13.8%	11.5%	13.8%	100.0%
Optimal :-) (t-1)	19	28	30	33	35	32	34	36	35	282
	6.7%	9.9%	10.6%	11.7%	12.4%	11.3%	12.1%	12.8%	12.4%	100.0%
Over consumption :-((t-1)	72	54	48	48	47	48	42	44	41	444
	16.2%	12.2%	10.8%	10.8%	10.6%	10.8%	9.5%	9.9%	9.2%	100.0%