Demand response as a common pool resource game: Nudges versus prices

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November 14, 2017

Preliminary document

Abstract

The aim of demand response is to make energy consumption more flexible during peak periods. Using a contextualised CPR framework, we study energy consumption choices. Subjects decide the consumption level of five activities during 10 periods. The total consumption of these activities is the CPR contribution, and payoffs depend on the amount consumed by the group. In the nudge treatment, subjects are nudged towards the socially optimal level of consumption using injunctive norms. The average consumption observed in the nudge treatment is used to calculate the tax implemented in the tax treatment. The objective is to quantify the nudge via an equivalent tax. The main hypotheses are: consumption choices will be lower in the treatment groups compared to the control groups; when the tax level is fixed according to the nudge result, consumption choices in the tax treatment will be equivalent to those in the nudge treatment. Across all 10 periods, consumption is significantly lower in the nudge treatment, and higher for control groups. In the tax treatment, consumption remains between the two at or slightly above the target. We conclude that the nudge treatment performs as well as an equivalent tax without the implied loss of welfare. When comparing decisions under the nudge and tax treatments to the control groups, the consumption decisions are significantly different from period 2 for the nudge and, consistently different from period 7 for the tax. We conclude that the nudge is understood and integrated into subjects' decision making quicker than an equivalent tax.

Keywords: common pool resource, laboratory experiment, incentives, nudge, tax

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1 Introduction

The cost of producing electricity is increasing, in particular on high demand days when older, less efficient power stations are used to meet the high demand. This increases both the financial cost of producing energy and its environmental cost. In addition, 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 (COM/2014/15, 2014). Given the greater cost of producing peak electricity and that renewable energy is, by definition, an intermittent source of energy, there is a need to have a more flexible residential energy demand, particularly during peak periods.

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 reflects the higher production costs. 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. Nudge based incentives go beyond simple information by changing the way the information is presented in order to exploit behavioural biases (Thaler and Sunstein 2008).

The principal objective of the present experiment is to use a contextualised common pool resource (CPR) game to compare the effect of nudges and taxes on subjects consumption choices in order to give a monetary value to the nudges. The secondary objective is to compare subjects' choices of which appliances to use and which electricity-consuming activities to take part in when faced with a need to reduce their demand. In doing so, we hope to respond to the following questions: Which interventions are more likely to increase socially optimal behaviour? How do people respond to nudges and taxes in an energy consumption context? What trade-offs do they make in terms of which electric appliances to use or not use? And finally, what is the 'price' of the nudge?

The remainder of this paper is set out as follows, the second section discusses the literature related to the research questions, the third section sets out the theory behind the CPR game used in the experiment, and the fourth section describes the experimental design. The fifth section gives the results and the final section discusses and concludes.

2 Related literature

The present experiment is related to the literature concerning the implementation of taxes and nudges in a laboratory setting, and to the literature on residential electricity field experiments.

In laboratory experiments, taxes 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 can be politically difficult to implement as well as costly, policy makers have also used non-price interventions to influence households to reduce their energy consumption, such as nudges. Nudges are designed to change a behaviour without altering the options available to them or adjusting their economic incentives (Thaler and Sunstein 2008). The use of social and injunctive norms can be considered as nudges.

Social norms provide individuals with a description of what others do, such as typical alcohol consumption, amount of exercise per week, or electricity consumption. According to the psychological literature on social norms, the context within which the norm is presented influences a persons behaviour (Maltby et al. 2012; Taylor et al. 2015). An injunctive norm adds an element of social approval or disapproval of the behaviour.

Delaney and Jacobson (2015) provide a direct comparison of price and non-price interventions in a CPR setting, as well as looking at the persistence of such effects once the interventions have been removed. They compare price (Pigouvian subsidy) and non-price (information, normative messaging and communication) interventions in a CPR experiment. They find that while all treatments result in an extraction level closer to the social optimum, the Pigouvian subsidy is the most effective, bringing extraction to slightly below the socially optimal level. With regard to the non-price incentives, each has a small effect on extraction level with normative messaging (both with and without communication) having the greatest effect of the non-price treatments.

The authors note that it is unusual that the normative treatment results in a small reduction in extraction level when compared to social 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; 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.

My and Ouvrard (2017) use a public good game to compare how subjects respond to a nudge and a tax according to their level of environmental sensitivity[1]. Subjects'

[1]Environmentally sensitivity is measured using the General Ecological Scale, see section 4 for details

are split into groups according to whether they are more or less environmentally sensitive than average and then are 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 of more environmentally sensitive subjects. My and Ouvrard (2017) find a higher level of contributions in the tax treatment for both types of group. However, the amount contributed in the tax treatment is not significantly different from that contributed in the nudge treatment. Interestingly, the authors find that the use of a nudge decreases (increases) the contributions of less (more) environmentally sensitive groups compared to the control groups.

The different incentives have been tested independently in field experiments in different geographical locations but are not often compared within the same experiment, under the same conditions. Mizobuchi and Takeuchi (2013) compare a financial incentive (comparable to a peak-time rebate) to the same financial incentive combined with socially comparative information. They find that the additional information on a households consumption relative to their neighbours does not result in a significantly larger reduction in consumption. In an Irish study, Carroll et al. (2014) test a combination of financial incentives and informative and comparative nudges and as such the effects of each cannot be separated.

In electricity consumption field experiments, social norms are used to incentivise a reduction in electricity consumption. Households are told how much they consume compared to the average consumption of their neighbourhood. However, Schultz et al. (2007) found evidence of a boomerang effect; upon being told that they are consuming below the average of their group, low-consuming households increased their consumption. There was a tendency to converge towards the average level of consumption. In pilot studies using Opowers Home Energy Report, a combination of both social norms, a description of a household's consumption compared to the average of their neighbourhood, and injunctive norms, the addition of a smiley face to the bills of those who consume less than average to promote social approval of this behaviour, are used to incentivise households to lower their electricity demand (Allcott 2011).

While taxes (or prices) and nudges have been tested previously in both laboratory and field experiments, few papers, to the authors' knowledge, have directly compared subjects' behaviour using clearly defined treatments. The present paper adds to the research by exploring demand side management via a contextualised common pool resource game: subjects are incentivised to reduce their consumption during a peak period taking into account the negative externalities resulting from overconsumption. In addition, the experimental design includes an element of a discrete choice experiment where subjects are asked to decide whether to use, or not, various electrical equipments which determines their consumption for the peak period.

on the questionnaire

3 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, distrubtion centres, transmisson 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 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).

3.1 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 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.

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

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:

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

The Nash equilbrium 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[2]:

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

4 Experimental Design

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

4.1 Participants and Procedure

The experiment took place during 12 sessions[3] in March and April 2017 at the Grenoble Applied Economics Laboratory (GAEL). Each session involved 20 subjects

[2]In the context of electricity consumption d is the higher price of electricity during peak periods.

[3]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 under the tax treatment.

(240 subjects in total) and lasted for one and a half hours. Table 1 shows the number of sessions, subjects and groups per treatment. The experiment was programmed using zTree software (Fischbacher 2007). Individual earnings ranged from 17€20 to 28€00 with average earnings across sessions of 22€30 (including a 10€ show-up fee). The majority of subjects were undergraduates students in various disciplines, 59% of were female subjects, and the average age across subjects was 22 years (see table 2).

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), an altruism questionnaire (Costa and McCrae 1992) and finally a demographic questionnaire [4]. 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.

Table 1: Number of subjects per treatment

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

Table 2: Description of subjects

Male	Undergraduate	Average age
42.5%	67%	22

4.2 Experimental parameters

In the experiment, subjects form groups of four ($n = 4$) for 10 periods ($t = 10$). Subjects remain in the same groups for the duration of the experiment. At the start of each period, subjects receive an endowment $e = 100$ ECU[5] which they must use to consume electricity (measured in energy units (EU)). In the control and nudge treatments

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

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

each EU costs 1 ECU ($c = 1$). The cost of each EU changes in the tax 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. Collectively subjects should each consume $x^{SO} = 15$ for an individual profit of 190 ECU.

At the beginning of each session, subjects randomly choose a subject number and a computer post. Once the subjects are seated, the experimenter reads aloud all instructions. These are also displayed on two screens at the front of the room which all subjects can see. After general instructions concerning confidentiality, anonymity of data and the code of conduct are given, the experimenter describes the context of the game.

The game concerns electricity consumption during 10 peak periods when the demand can be greater than production. The subjects are placed into the same group of 4 for the duration of the experiment. This group makes up an electricity consumption system of four households. In this context the demand response challenge is represented as a repeated CPR game.

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 3 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 (a lower monetary gain). The greater the total consumption of the group, the greater the reduction in comfort.

Given the levels of consumption available, subjects can only choose to consume energy units in increments of 5. As such 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[6] 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.

4.2.1 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.

[6]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 author.

Table 3: Electricity consumption choices

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

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.

4.2.2 Tax treatment

In the tax treatment, subjects are told that power cuts can be avoided by incentivising consumers to consume less during peak periods by increasing the price of electricity. The tax for this treatment is calculated with respect to the average levels of consumption observed in the nudge treatment. The goal is to compare whether the tax results in the same level of consumption as the nudge when that is its objective. Below in the results section, 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 tax is calculated such that the Nash equilibrium consumption level under tax, $x_i^{NE,T} = 20$.

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

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

In this treatment the subjects maximises:

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

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[7]. The feedback given at the end of each period is the same as above; the subject's level of consumption and their earnings for that period.

4.3 Hypotheses

Following the review of the literature and the design of the experiment, the following hypotheses have been formulated:

H1 Consumption choices in the nudge treatment will be lower than in the control treatment.

H2 Consumption choices in the tax treatment will be lower than in the control treatment.

H3 When the tax level is fixed according to the nudge result, consumption choices in the tax treatment will be equivalent to those in the nudge treatment.

H4 Subjects who receive 'happy face' feedback will not change their consumption in following period (those who consume the optimal amount or less).

H5 Subjects who receive 'sad face' feedback will lower their consumption in following period (those who consume more than the optimal amount).

H6 More environmentally sensitive and altruistic subjects will consume less than less environmentally sensitive and altruistic subjects in all treatments.

H7 More environmentally sensitive subjects will consume less in the nudge treatment than in the tax treatment.

5 Results

In this section we describe the results of the experiment beginning with descriptive statistics and a graphical analysis of group level consumption decisions, with non-parametric testing. Next the individual choices of subjects are analysed, for all treatments and specifically for the nudge treatment according to the message received. We then look at the results of the questionnaires and how individual consumption decisions vary according to their results. Finally, we consider the equipment choices made by subjects.

[7]This is comparable to current tariffs proposed by EDF. According to the tariffs available at the time of experimentation, the highest peak price is approximately 3.5 times the standard tariff (EDF 2016).

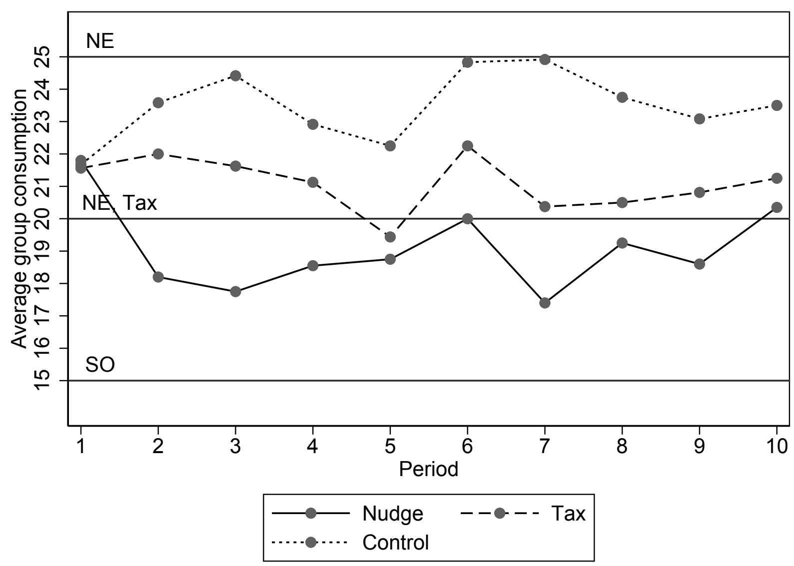
5.1 Average consumption at the group level

The average group consumption per period by treatment is summarised in table 4 and represented graphically in figure 1. All groups begin at a similar level of consumption, then as the game progresses, consumption is consistently lower in the nudge treatment, and higher for control groups. In the tax treatment, consumption remains between the two, at or slightly above the Nash equilibrium amount of 20.

Table 4: Average consumption per period by treatment

	Period										
Treatment	1	2	3	4	5	6	7	8	9	10	Total
Nudge	21.80	18.20	17.75	18.55	18.75	20.00	17.40	19.25	18.60	20.35	19.07
Tax	21.56	22.00	21.63	21.13	19.44	22.25	20.38	20.50	20.81	21.25	21.09
Control	21.67	23.58	24.42	22.92	22.25	24.83	24.92	23.75	23.08	23.50	23.49

Figure 1: Average consumption per period by treatment



Tables 5 provides the p-values of the Kruskal-Wallis and Wilcoxon rank-sum tests of whether independent samples originate from the same distribution, overall and by period.

In bold are p-values<0.05, resulting in a rejection of the null hypotheses that the samples are not different from one another. Overall, all samples are different from one another. In the first period, the null hypothesis of same distributions cannot be rejected therefore we can conclude that the samples are not significantly different in the first period. 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

Table 5: By period comparison of treatment samples (p-values)

	Period										
	1	2	3	4	5	6	7	8	9	10	Overall
N=T=C	0.9899	**0.0001**	**0.0001**	**0.0291**	**0.0197**	**0.0428**	**0.0001**	**0.0221**	**0.0007**	**0.0437**	**0.0001**
N=T	0.9083	**0.0004**	**0.0086**	0.0732	0.2947	0.2560	**0.0300**	0.4215	**0.0275**	0.6960	**0.0046**
N=C	0.9216	**0.0005**	**0.0001**	**0.0147**	**0.0104**	**0.0160**	**0.0000**	**0.0111**	**0.0008**	**0.0256**	**0.0001**
T=C	0.9194	0.2027	**0.0293**	0.2842	**0.0313**	0.1181	**0.0042**	**0.0275**	**0.0127**	**0.0278**	**0.0035**

consumption in the first period be similar between the nudge and control groups. From period 2, there is a significant and permanent effect of the nudge policy as the consumption decisions under the nudge treatment are different to those of control groups.

In the tax treatment, subjects are aware of the tax amount prior to any decision making. We would therefore expect there to be a significant difference between consumption decisions in the tax treatment compared to control groups from the first period. However, the average group consumption is only consistently and significantly different from the seventh period. This suggests that it takes several periods for the subjects to integrate the tax in their decision making. Therefore, a tax that is designed to achieve the same results as a nudge policy does so but more slowly.

Given that the tax 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 between the nudge and tax treatments. However, we see significantly different levels of consumption in periods 2 and 3, again suggesting that subjects do not immediately integrate the tax into their decision making.

In table 6 average group consumption decisions are compared to the Nash equilibrium and social optimum for each treatment by period using a Wilcoxon signed rank test. As can be seen from the results, in the nudge treatment, average group consumption is always significantly different from the social optimum of 15 and the Nash equilibrium of 25. Average consumption for control groups never reaches the social optimum but in 7 of 10 periods it is not significantly different from the Nash equilibrium. These results, along with those in table 5 allows us to conclude that the nudge has a significant effect on average group consumption and moves subjects closer to consuming the socially optimal amount than in the absence of treatment.

The test is also performed on the results of average group consumption under the tax treatment. In all but 3 periods, including the first two, average group consumption is not significantly different from 20. A consumption choice of 20 is the amount that the tax incentivises subjects to choose. The tax appears to be the most efficient instrument at incentivising subjects to consume a predefined amount. However, given that the first two periods are significantly different from 20, it can be concluded that the tax takes more time to understand than the nudge treatment.

In figure 2 the average consumption for each group per period by treatment is shown. Horizontal lines show the social optimum (15 EU) and the Nash equilibrium (25 ECU) consumption amounts for the nudge treatment and control groups, and the

Table 6: Comparison of average group consumption to social optimum and Nash equilibrium (*p*-values)

	Period										
	1	2	3	4	5	6	7	8	9	10	Overall
N=15	**0.0000**	**0.0002**	**0.0048**	**0.0008**	**0.0004**	**0.0006**	**0.0095**	**0.0009**	**0.0006**	**0.0001**	**0.0000**
N=25	**0.0025**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0005**	**0.0000**	**0.0000**	**0.0000**	**0.0002**	**0.0000**
T=20	**0.0370**	**0.0139**	0.2290	0.3203	0.4250	**0.0238**	0.9700	0.5452	0.1491	0.1505	**0.0001**
C=15	**0.0007**	**0.0006**	**0.0006**	**0.0007**	**0.0007**	**0.0006**	**0.0006**	**0.0006**	**0.0007**	**0.0006**	**0.0000**
C=25	**0.0083**	0.3314	0.5642	0.1897	**0.0243**	0.8416	0.9772	0.1946	**0.0329**	0.1665	**0.0001**

Nash equilibrium (20) for the tax treatment. There is evidence of a treatment effect in the nudge treatment as post-feedback, the average consumption levels decrease. Across periods, average consumption levels are fairly stable in the nudge treatment (from period 2 onwards). In the control groups, there is evidence of a slight increase in average consumption levels towards the Nash equilibrium of 25.

Table 7 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 allows for heterogeneous subjects and is more efficient than fixed effects estimation. In addition, 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 of the control groups. Models 1 and 2 show a clear significant effect of both the nudge and tax treatments compared to the control groups. In models 3-6, dummy variables are added to specify whether the group under or over consumed compared to the optimal consumption in their treatment. In addition, in models 5 and 6 these dummies are interacted with the treatment variables in order to identify treatment effects. At the group level, there is no significant effect on consumption due to under- or over-consuming in the previous period.

5.2 Average consumption at the individual level

Table 8 shows the regression estimates of random effects models of treatment and covariate on individual consumption choice. Model 1 shows a significant treatment effect. 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. Models 3-6 show, to differing degrees of significance, that individuals who under-consumed in *t-1*, continue to under-consume in t compared to optimally consuming individuals. Those who over-consume in *t-1* continue to do so compared to optimally consuming individuals. On interacting under- and over-consumption with treatment variables, no significant effects are found.

The estimates of the effect of the message received in the nudge treatment on individual consumption choice are shown in table 9. Subjects who under consume receive a

Figure 2: Average consumption per period per group by treatment

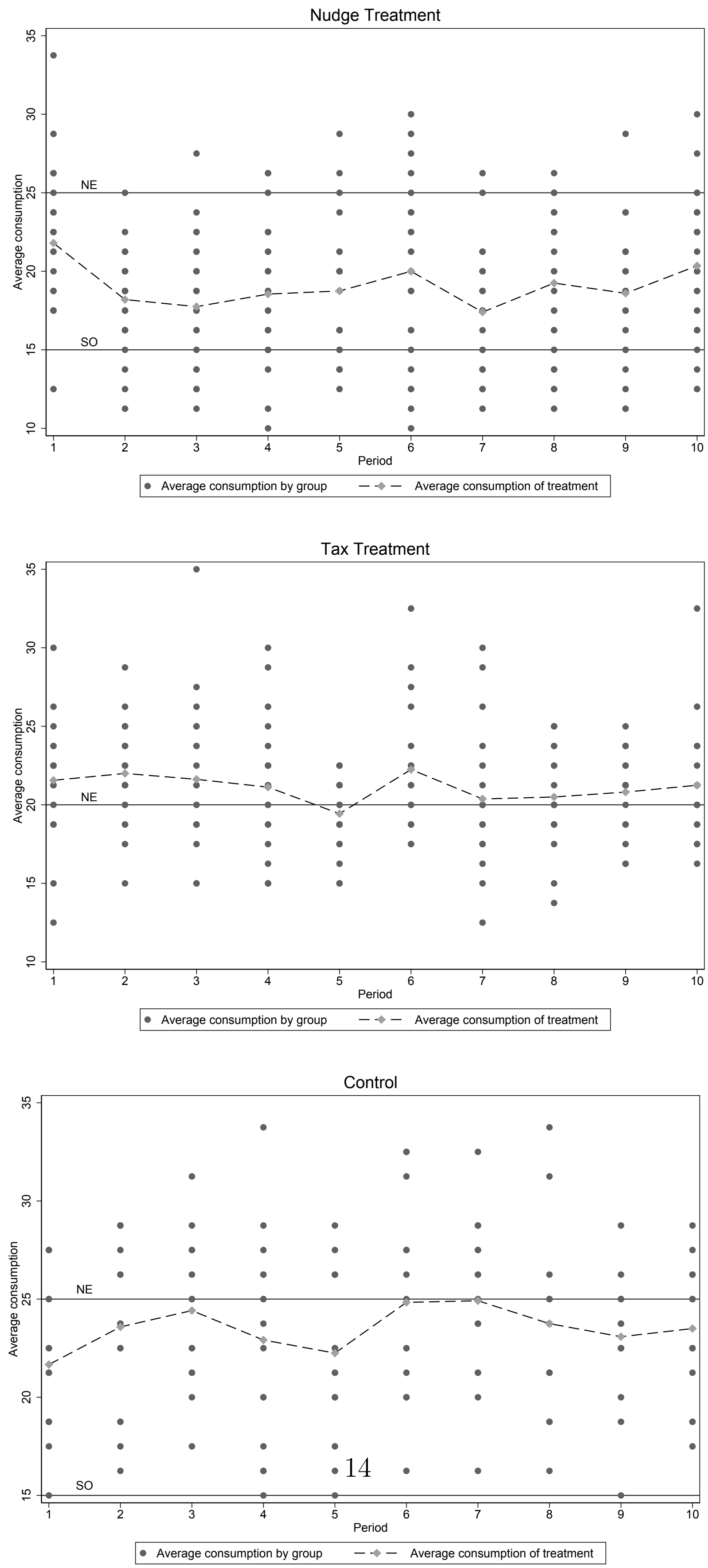


Table 7: Average group consumption (random effects estimation)

	(1)	(2)	(3)
Nudge	-4.427***	-4.724***	-5.785**
	(0.829)	(0.803)	(1.985)
Tax	-2.398***	-2.239**	-2.552
	(0.701)	(0.715)	(1.998)
Group under consumed (t-1)		-0.784	-0.063
		(0.683)	(0.921)
Group over consumed (t-1)		0.344	-0.144
		(0.590)	(1.898)
Nudge*Under (t-1)			-2.036
			(1.293)
Nudge*Over (t-1)			1.568
			(2.078)
Tax*Over (t-1)			-0.262
			(2.091)
Constant	23.492***	23.360***	23.834***
	(0.606)	(0.795)	(1.816)
Observations	2400	2160	2160

Standard errors in parentheses

Robust standard errors clustered by group

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

Table 8: Average individual consumption (random effects estimation)

	(1)	(2)	(3)	(4)	(5)	(6)
Nudge	-4.427***	-5.655***	-3.899***	-4.802***	-3.204**	-4.050**
	(0.829)	(0.952)	(0.720)	(0.840)	(1.181)	(1.314)
Tax	-2.398***	-1.799*	-0.843	-0.062	0.084	0.705
	(0.701)	(0.901)	(0.636)	(0.872)	(1.164)	(1.326)
Profit in t-1		0.033***		0.037***		0.036***
		(0.005)		(0.007)		(0.007)
Under consumed (t-1)			-2.091***	-1.619**	-3.763*	-3.085
			(0.584)	(0.572)	(1.852)	(1.930)
Over consumed (t-1)			3.589***	3.342***	4.918***	4.568***
			(0.496)	(0.483)	(1.102)	(1.063)
Nudge*Under (t-1)					1.552	1.755
					(2.009)	(2.079)
Tax*Under (t-1)					2.186	1.607
					(2.044)	(2.113)
Nudge*Over (t-1)					-1.124	-1.377
					(1.329)	(1.314)
Tax*Over (t-1)					-2.237	-1.516
					(1.350)	(1.315)
Constant	23.492***	18.682***	21.294***	15.785***	20.521***	15.131***
	(0.606)	(1.189)	(0.672)	(1.494)	(1.108)	(1.761)
Observations	2400	2160	2160	2160	2160	2160

Standard errors in parentheses

Robust standard errors clustered by group

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

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 t-1. 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 [8].

Table 9: Effect of message on individual consumption in nudge treatment

	(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

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

5.3 Questionnaire results

5.3.1 General Ecological Behaviour

The GEB questionnaire is used to measure subjects' environmental sensitivity following My and Ouvrard (2017). In their public good experiment, the authors find that subjects react to a nudge depending on their level of environmental sensitivity. Of the 28 items, the mean score per item is 3.34 (std. dev. = 0.22). Cronbach's $\alpha = 0.73$. The GEB scale is therefore acceptable.

The average sensitivity level of subjects overall, and per treatment is described in table 10, followed by the between treatments tests in table 11. While the average level of environmental sensitivity appears to be similar between treatments, the p-values tell

[8]These variables did not show significant effects in regression on full dataset and so were not included in the above tables

us that the levels are not statistically different from one another between only the nudge and the tax treatments.

Table 10: Generalised Ecological Behaviour Scale

Nudge	Tax	Control	Overall
108.8	106.5	107.1	107.6
(10.25)	(10.64)	(9.61)	(10.28)

Standard deviations are in brackets.

Table 11: GEB: Wilcoxon rank-sum test (Between treatment p-values)

	Tax	Control
Nudge	0.0001	0.0000
Tax		0.7534

Table 12 shows the average consumption decisions of individuals in each treatment according to their sensitivity to the environment. High environmental sensitivity is classed as greater than the average of the sample [9]. As can be seen from the table, in the nudge and control groups, more environmentally sensitive subjects choose to consume less than less environmentally sensitive subjects across all treatments. The differences in individual consumption by environmentally sensitivity are only statistically significant in the nudge treatment as seen in table 13. We can conclude that, while more environmentally sensitive subjects choose to consume less across all treatments, the nudge treatment makes best use of environmental sensitivity to separate the consumption decisions of different subject types.

Table 12: Average individual consumption by treatment and by environmental sensitivity

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

5.3.2 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.

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

Table 13: Average consumption by treatment and by environmental sensitivity (p-values)

		High environmental sensitivity		
		Nudge	Tax	Control
	Nudge	0.0000		
Low environmental sensitivity	Tax		0.2036	
	Control			0.1770

The average altruism scores are reported in table 14 across all subjects and by treatment and the associated p-values in table 15. The average scores on the altruism tests are significantly different across the nudge and tax, and the nudge and control treatments. They are not significantly different between the tax and control treatments.

Table 14: Altruism Questionnaire Results

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

Table 15: ALT: Wilcoxon rank-sum test (Between treatment p-values)

	Tax	Control
Nudge	0.0000	0.0000
Tax		0.5779

Table 16 shows the individual consumption decisions by treatment according to each subject's level of altruism. High altruism is a level greater than the average of the sample [10]. In the nudge treatment highly altruistic individuals choose to consume less than less altruistic individuals. The levels are similar in the control groups, and the opposite is observed in the tax 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.

5.3.3 Risk attitudes

In the second phase of the experiment, subjects completed a Holt and Laury (2002) test of aversion to risk. As expected, the majority of subjects are risk averse. Figure 3 displays the percentage of subjects by risk attitude and by treatment. In the nudge and tax treatment, 80% of subjects are risk averse. In the control groups, there is a greater percentage of risk takers compared to the two other treatments.

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

Table 16: Average individual consumption by treatment and by altruism level

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

Table 17: Average consumption by treatment and by altruism level p-values

		High level of altruism		
		Nudge	Tax	Control
	Nudge	0.0000		
Low level of altruism	Tax		0.6936	
	Control			0.6117

Figure 3: Risk attitudes by treatment

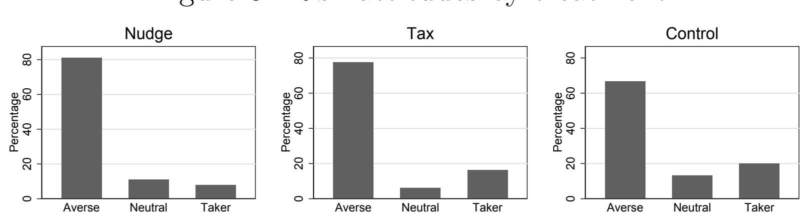


Table 18 provides the average individual consumption choices by treatment, and table 19 the associated p-values. In the nudge treatment, there is little difference in the average consumption choices by risk attitude and as reflected in the p-values, these differences are not significant. In the tax treatment and control groups, the difference between the average consumption decisions of risk neutral subjects compared to risk averse and risk takers is significantly larger.

Table 18: Average individual consumption choices by risk attitude

	Averse	Neutral	Taker	Total
Nudge	19.10	19.18	18.56	19.07
Tax	20.48	24.80	22.62	21.09
Control	23.00	27.00	22.79	23.49
Total	20.42	22.96	21.70	

Table 19: Average individual consumption choices by risk attitude (p-values)

	Nudge		Tax		Control	
	Neutral	Taker	Neutral	Taker	Neutral	Taker
Averse	0.9483	0.6076	0.0000	0.0012	0.0009	0.7141
Neutral		0.6429		0.1172		0.0013

5.4 Equipment Choices

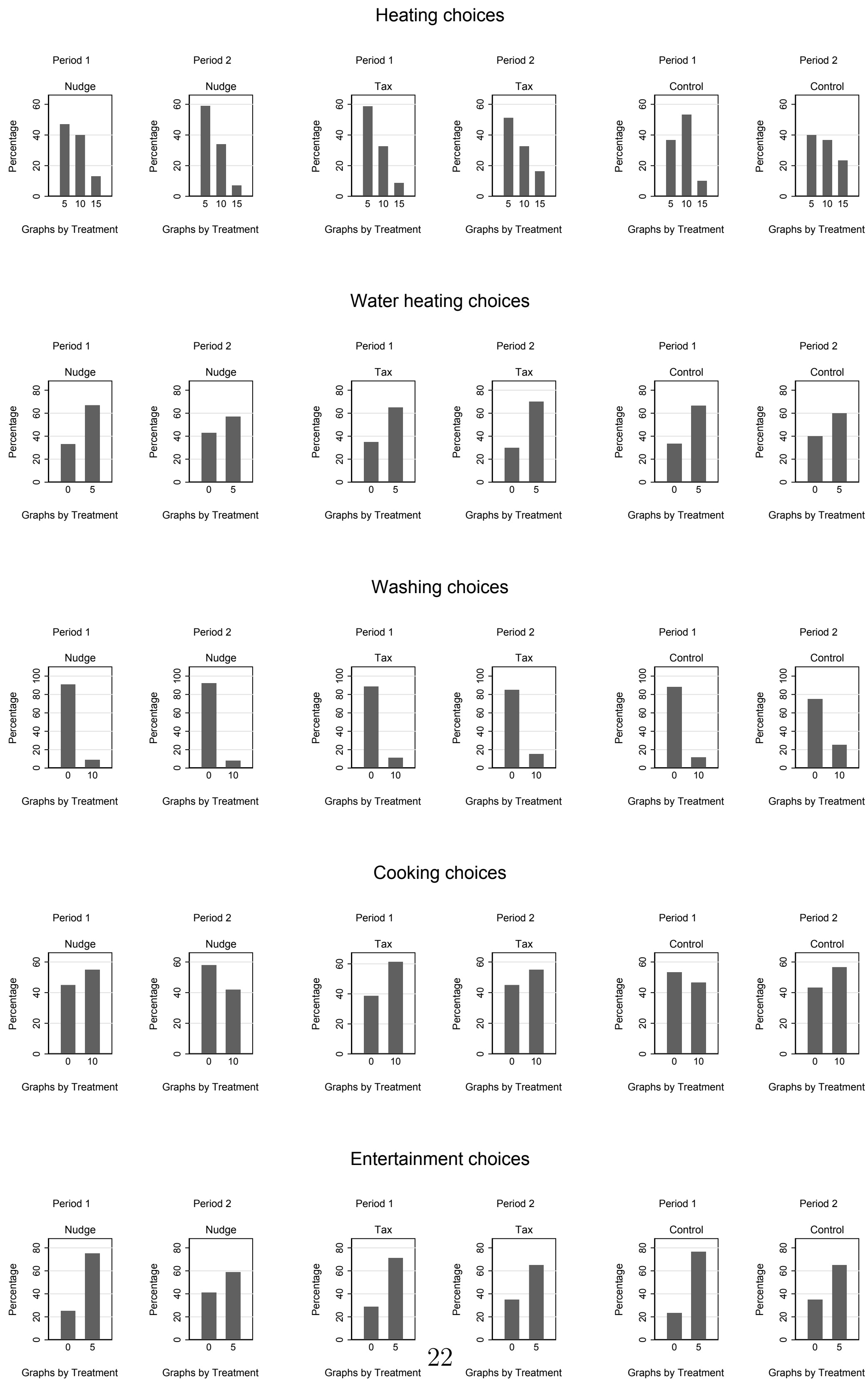
This section looks at the choices of subjects with regard to which electricity consuming activities they are willing to shift during the peak period. Figure 4 shows the percentage of subjects who chose each level of consumption for each of the five electricity consuming items by treatment for periods 1 and 2. Only periods 1 and 2 are considered as these correspond to the initial period and the first period post-feedback. The consumption level, measured in energy units (EU), is plotted on the x-axis.

Across treatments, subjects were willing to lower their heating. More subjects chose to lower their heating by one or two degrees rather than keep it at the same temperature. In the nudge treatment more subjects chose to lower their heating by 2 after the feedback on their consumption choice. In the tax treatment, an increase in the percentage of subjects choosing to keep their heating at the same temperature can be observed.

In all treatments and for each period, approximately 60% of subjects chose to leave their water heater turned on. In both the nudge treatment and the control, more subjects chose to turn off their water heater after receiving feedback. The opposite happened in the tax treatment.

Use of a washing machine or dishwasher is the activity that subjects are most willing to shift. Around 80% of subjects choose to turn off these machines across treatments.

Figure 4: Consumption choices by treatment (periods 1 and 2)



Across treatments, the proportion of subjects using or not their washing machines remains stable after feedback is received.

Subjects are fairly evenly split in their willingness to shift their cooking activities during the peak periods. In both the nudge and the tax treatments, after receiving feedback, more subjects shifted their cooking activities than prior to feedback. More subjects chose to turn off cooking appliances rather than use them during the second peak period in the nudge treatment compared to the tax treatment.

Electricity consuming entertainment activities appear to be the activity that subjects are least willing to shift, with upwards of 60% of subjects choosing to turn on their televisions and computers. Post-feedback, this percentage decreases as more subjects turn off their entertainment items. The difference is most pronounced in the nudge treatment.

6 Discussion and conclusion

The experiment described in this paper explored subjects responses to price and nudge-based interventions in a contextualised common pool resource game. The experimental design allows for comparison of behaviour under a nudge and an equivalent tax. In particular, the experimental design provides an opportunity to examine subjects' consumption choices regarding the use of different appliances. The results of the experiment may be of interest to policy makers when considering the implementation of a nudge or a tax based intervention designed to reduce households energy consumption.

The principal result of the experiment is that both treatments, nudge and tax result in a reduction in consumption compared to when no intervention is present. Both hypothesis 1 and 2 are validated. Subjects consume the lowest amount in the nudge treatment. This is to be expected as the nudge target is a consumption of 15 EU, whereas the tax is designed to incentivise a consumption level of 20 EU. The design of the experiment allows for an evaluation of the economic value of the nudge compared to its equivalent tax. We can conclude that this nudge in itself is not sufficient to achieve the social optimum, however it performs as well as an equivalent tax without the loss of welfare implied by a tax.

Given that the tax is designed based upon the mean level of consumption observed in the nudge treatment, we expect subjects to consume the same level as under the nudge treatment. However, from the results, we see that the level of consumption in the nudge and tax treatments are not significantly different from period 4 onwards. We can conclude that the tax takes longer than the nudge to achieve the desired outcome as subjects take longer to integrate the tax into their decision making than they do for the feedback in the nudge treatment. The hypothesis that consumption will be similar in the nudge and tax treatments is rejected.

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' behaviour. Subjects who under or optimally (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 the nudge may serve to reinforce behaviours that are already present and merits further research.

Similarly to My and Ouvrard (2017), we evaluated subjects level of environmental sensitivity. While in all treatments, more environmentally sensitive subjects consumed less than less environmentally sensitive subjects at an individual level, the difference is only statistically significant in the nudge treatment. In line with My and Ouvrard (2017), we can also conclude that subjects' behaviour in response to a 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 tax treatment. This difference is greater for more environmentally sensitive subjects. We also assessed subjects' level of altruism. More altruistic subjects consumed less in the nudge treatment; subjects' behaviour in response to the nudge also depends on their altruism. Interestingly, in the tax treatment highly altruistic subjects consumed more than less altruistic subjects. This might suggest that the presence of the tax crowds out subjects' willingness to reduce their consumption. However the difference is only significant in the nudge treatment. This provides evidence to confirm hypothesis 6 in the nudge treatment. Hypothesis 7 is also confirmed.

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. Given the design of the experiment provides us with consumers choice of equipment use across 10 periods, we plan to further analyse the data using discrete choice methodology in order to explore how subjects consumption choices differ by treatment and during the course of the game.

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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.