Cross Elasticities in Dual Discounting

Pre-Analysis Plan

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1 Introduction

This document presents the pre-analysis plan for the preregistered experiment with the ID *AEARCTR-0015423* in the AEA RCT Registry.

The pre-analysis plan is structured as follows: In Section 2 we present our *Primary Hypothesis*, followed by *Secondary Hypotheses* and further *Explorative Hypotheses*. The *Primary Hypothesis* of our study is the fundamental outcome that we are interested in: The existence and relevancy of cross elasticities in the context of dual discounting of market and non-market environmental goods. The *Secondary Hypotheses* consist of additional outcomes of interest. The *Explorative Hypotheses* are hypotheses that are experimental in nature and as such not informative for the success of the study. In Section 3 we present details of our analyses, such as descriptions of variables, the general statistical specifications and the specific equations and models that we use to test our hypotheses.

2 Hypotheses

2.1 Primary Hypothesis

The primary focus of this study is to test for the role of cross elasticities in dual discounting. We hereby extend prior work by Venmans and Groom (2021), who have conducted a variant of our analysis only for environmental domains and without being able to identify the cross-elasticity (η_{EC}) in the environmental domain and full dual discount rate formulas more generally. The theoretical background for our analysis is given by the following two extended formulations of the classic Ramsey Rule that show how market goods and non-market environmental goods should be discounted at separate rates (e.g., Weikard and Zhu, 2005; Hoel and Sterner, 2007; Traeger, 2011; Baumgärtner et al., 2015)[1]:

$$SDR_C = \delta + \eta_{CC} g_C + \eta_{CE} g_E \tag{1}$$

$$SDR_E = \delta + \eta_{EE} g_E + \eta_{EC} g_C \tag{2}$$

Our main test of interest lies in specifying dual discount rates and thus in the existence and relevance of the cross elasticities (η_{CE}, η_{EC}), which have not been explicitly considered or identified in prior experimental or empirical work.[2] Rejecting the hypothesis that these elasticities jointly equal zero would provide a rationale for the inclusion of cross elasticities in good-specific discounting formulations. Accordingly, our primary hypothesis is as follows:

$$H_0^1 : \eta_{CE} = \eta_{EC} = 0$$

[1] An alternative approach is to use relative price change (RPC) adjustments in each period, to compute consumption-equivalents, which then allows using a single discount rate (e.g., Weikard and Zhu, 2005; Baumgärtner et al., 2015; Drupp et al., 2024).

[2] To keep our extension otherwise comparable to Venmans and Groom (2021), we also consider a simple setting of equal preferences and constant growth rates for our main analyses and abstract from discount rate transition dynamics that are theoretically studied in Traeger (2011) or Zhu et al. (2019). In our *Explorative Hypotheses* we explicitely consider the latter case.

2.2 Secondary Hypotheses

In addition to the joint existence of the cross elasticities, we are interested in identifying them separately:

$$\forall x \in \{\eta_{CE}, \eta_{EC}\} : H_0^{2;x} : x = 0$$

To specify the full dual discounting equations (1 and 2), we will furthermore test whether the other parameters differ significantly from zero[3]:

$$\forall x \in \{\delta, \eta_{CC}, \eta_{EE}\} : H_0^{3;x} : x = 0$$

Additionally, we are interested in testing the following equalities:

$$H_0^4 : \delta_C = \delta_E$$
$$H_0^5 : \eta_{CC} = \eta_{EE}$$
$$H_0^6 : \eta_{CE} = \eta_{EC}$$
$$H_0^{7,a} : \text{mean}(SDR_C) = \text{mean}(SDR_E)$$
$$H_0^{7,b} : \text{var}(SDR_C) = \text{var}(SDR_E)$$

H_0^4 investigates the standard framework of common time preferences across market and non-market domains ($\delta = \delta_C = \delta_E$), as embedded in the extended Ramsey Rule. Venmans and Groom (2021), across different environmental domains, as well as Howard (2013), across

[3]Note that, in general, both the elasticities and cross-elasticies are variables that may change along the consumptions levels of market and non-market goods. We will here, as in most applications and empirical analyses, treat them as constant parameters and investigate the plausibility of this assumption in the *Explorative Hypotheses*. In the case of non-constant elasticities our parameter estimates reflect a linear approximation or weighted average of the varying elasticities. A few studies examine non-constant elasticities, for instance as a result of subsistence consumption (e.g., Drupp, 2018), environmental scarcity (e.g., Conte et al., 2025), or differences in incomes or technologies (e.g., Barbier et al., 2017).

private and social domains, find some evidence that pure time preference rates may differ. In our model, described in Section 3.3, we denote $\delta_{\Delta E}$ as the difference to δ_C and therefore, in implementation, we test $H_0^4 : \delta_{\Delta E} = 0$, which is equivalent.

H_0^5 investigates whether preferences for consumption smoothing (or inequality aversion) across periods, evaluated for the primary good domain, differ across market and non-market (environmental) domains[4]. Venmans and Groom (2021) find that inequality aversion differs across contexts, but only investigate this for environmental domains. Howard (2013) finds some indication that consumption smoothing varies across private and social domains, but not consistently so across model specifications.

H_0^6 investigates whether the cross elasticities differ from one another. As no prior study has investigated these cross elasticities, we have no literature benchmark to compare it to. In the standard workhorse model of constant-elasticity-of-substitutions (CES) preferences, these two differ due to (a) the utility share parameters, and (b) the level of market, respectively non-market goods.

$H_0^{7,a}$ investigates whether the means of the observed dual discount rates coincide, and it thus effectively tests whether there are is any relative price change (RPC) effect between non-market vis-à-vis market goods implicit in respondent's choices. $H_0^{7,b}$ investigates whether the variances between the dual discount rates differ. This could indicate whether there is more agreement on intertemporal decisions involving market consumption goods or environmental non-market goods, or—conversely—more polarization.

2.3 Explorative Hypotheses

Apart from our primary and secondary hypotheses, we seek to (a) interpret our data and results in the context of the workhorse parametric setting of CES-CIES preferences, and (b) explore the heterogeneity within our data.

[4]Note that we elicit discount rates for two different environmental domains in our experiment–forst and air quality–but treat them as a composite good in our main analyses. In the *Explorative Hypotheses* we disentangle the estimates for the different domains.

Isoelastic utility

Our analysis up to this point has considered a generic utility function $U(C, E)$ and did not impose a specific functional form. In this section, we introduce more structure by investigating the workhorse case of CES-CIES preferences. To this end, we test the model-specific parameters and check the plausibility of the imposed model structure by conducting tests of internal consistency and testing the central assumptions of isoelastic preferences.

The case of CES-CIES preferences assumes that preferences are isoelastic both across goods and across time, as studied in e.g. Hoel and Sterner (2007), Gollier (2010), Traeger (2011) and Zhu et al. (2019), with the following utility function:

$$U(C, E) = \frac{1}{1-\frac{1}{\gamma}} \left[\alpha C^{\frac{\sigma-1}{\sigma}} + (1-\alpha)E^{\frac{\sigma-1}{\sigma}}\right]^{\frac{(1-\frac{1}{\gamma})\sigma}{\sigma-1}}, \tag{3}$$

where σ is the constant elasticity of substitution (CES), γ is the constant intertemporal elasticity of substitution (CIES) and $\alpha \in [0, 1]$ is the weight of the market consumption good[5]. The dual discount rates can then be formulated with distinct overall growth and real substitution terms (Traeger, 2011; Zhu et al., 2019):

$$SDR_C = \delta + \frac{1}{\gamma}\left[\lambda g_C + (1-\lambda)g_E\right] + \frac{1}{\sigma}(1-\lambda)\left[g_C - g_E\right] \tag{4}$$

$$SDR_E = \delta + \frac{1}{\gamma}\left[\lambda g_C + (1-\lambda)g_E\right] - \frac{1}{\sigma}\lambda\left[g_C - g_E\right], \tag{5}$$

where $\lambda \in [0, 1]$ is the value share of market goods vis-à-vis non-market environmental goods[6]. Here, the CIES parameter, γ, moderates the *overall growth effect*, while the CES parameter, σ, moderates the *real substitution effect* (Traeger, 2011). Importantly, the CES-CIES model reflects discounting transition dynamics through the time-dependent value share parameter

[5] For the case of perfect intertemporal substitution of aggregate consumption, we have $\gamma \to \inf$ and Eq. (3) collapses to the standard CES utility function: $U(C, E) = \left(\alpha C^{\frac{\sigma-1}{\sigma}} + (1-\alpha)E^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$.

[6] In general, the value share, λ, depends on the utility share of both goods, their time-dependent consumption levels and the degree of substitutability, see Traeger (2011).

λ. Depending on the values of the CES parameter, σ, and the CIES parameter, γ, our observed—and assumed to be constant—dual social discount rates either correctly reflect constant rates, or upper- or lower bounds of the social discount rates for the last period of our SWF.[7] The same argument holds for the parameter estimate of the value share λ.

We first conduct hypotheses for the parameters of Equations (4) and (5) before testing for internal consistency and the isoelastic model assumptions. To this end, note that the RPC equation in this model is given by

$$\Delta SDR = SDR_C - SDR_E = \frac{1}{\sigma}(g_C - g_E) = RPC, \tag{6}$$

and indicates the extent to which environmental good values (such as willigness-to-pay estimates) need to be adjusted over time, using RPC adjustments, in case a single social discount rate ought to be used (e.g., Drupp et al., 2024, 2025). We estimate the CES parameter σ of this equation to test the hypotheses of perfect substitutability and of the prominent knife-edge case of Cobb-Douglas substitutability:

$$H_0^{8,a} : \frac{1}{\sigma} = 0$$
$$H_0^{8,b} : \sigma = 1$$

We then seek to retrieve the remaining CIES parameter γ, and the value share parameter λ, of Equation (4) to test the following hypotheses:

$$H_0^{9,a} : \gamma = 1$$
$$H_0^{9,b} : \gamma = \sigma$$
$$H_0^{10,a} : \lambda = 0$$
$$H_0^{10,b} : \lambda = 1,$$

[7] This is the case as our observed discount rate, which is an aggregate over all periods, can be interpreted as the geometric mean of the time-varying discount rates.

which inform us whether steady state discount rates are constant or time-varying and whether the value share parameter λ already reached one of the two possible long run values, in case the discount rates are not constant in the steady state. Next, we want to check the internal consistency of the model by testing whether theoretically proposed equivalences hold. To this end, note that the RPC Equation (6) can also expressed as a linear combination of growth-weighted own and cross elasticities, which yields the following relationship (Baumgärtner et al., 2015):

$$\frac{1}{\sigma} = (\eta_{CC} - \eta_{EC}) = (\eta_{EE} - \eta_{CE})$$

Therefore, the following hypothesis should not be rejected if the isoelastic model structure plausibly describes our data:

$$H_0^{11} : (\eta_{CC} - \eta_{EC}) = (\eta_{EE} - \eta_{CE})$$

Similarly, we can test the following hypotheses that show whether the parameter estimates that we retrieve for γ and λ are independent from the good-specific discounting equation through which we estimate them:

$$H_0^{12} : \gamma_C = \gamma_E$$
$$H_0^{13} : \lambda_C = \lambda_E,$$

where γ_C and λ_C denote the estimates retrieved through the consumption discount rate Equation (4) and γ_E and λ_E denote the estimates retrieved through the environmental discount rate Equation (5).

Finally, we can test if the model assumption of constant (intertemporal) substitution elasticities are plausible by investigating whether our estimates of the CES and CIES parameters vary with the magnitude of the two growth rates. For the CES parameter, σ, we use a quadratic specification of the RPC equation, described in Section 3.3, where $\sigma_{X;2}$ denotes the coefficient on the quadratic growth term of good X, to the test:

$$H_0^{14,a} : \sigma_{C;2} = 0$$
$$H_0^{14,b} : \sigma_{E;2} = 0$$

For the CIES assumption, we investigate whether the sum of the elasticities η_{CC} and η_{CE} (or η_{EE} and η_{EC}), which equals the inverse of the CIES parameter, as we show in in Section 3.3, is sensitive to the magnitude of the growth rates by testing the following hypotheses through our quadratic model specificiation described in 3.3:

$$H_0^{15,a} : \eta_{CC;2} + \eta_{CE;2} = 0$$
$$H_0^{15,b} : \eta_{EE;2} + \eta_{EC;2} = 0$$

Heterogeneity analyses

We aim to explore heterogeneity in our data while noting potential limits to these analyses due to statistical power constraints.

In our experimental setting, we confront participants with both positive and negative growth rates for both goods. We denote positive growth for good X by X_p, negative growth by X_n and test the following hypotheses for all $X, Y \in \{C, E\}$ and $X \neq Y$:

$$H_0^{16;XX} : \eta_{XX}^{X_p} = \eta_{XX}^{X_n}$$
$$H_0^{17;XY} : \eta_{XY}^{Y_p} = \eta_{XY}^{Y_n}$$
$$H_0^{18;XY} : \eta_{XY}^{X_pY_p} = \eta_{XY}^{X_pY_n} = \eta_{XY}^{X_nY_p} = \eta_{XY}^{X_nY_n}$$

Similarly, we can test if the elasticities are non-constant i.e. if they differ depending on the magnitude of growth. We investigate this possibility by adding quadratic growth terms into our model and testing whether they produce identifiable parameters by testing:

$$\forall x \in \{\eta_{CC;2}, \eta_{EE;2}.\eta_{CE;2}.\eta_{EC;2}\} : H_0^{19;x} : x = 0$$

We also aim to explore differences in the main parameter estimates between the two environmental goods scenarios in our experiment by testing:

$$\forall x \in \{\delta_E, \eta_{EE}.\eta_{CE}.\eta_{EC}\} : H_0^{20;x} : x^{Forest} = x^{AirQuality}$$

Finally, we seek to explore differences in parameter estimates based on demographic information and other economic preferences collected as part of the survey module at the end of the experiment, but do not specify hypotheses for the breadth of potential relationships.

3 Details on Analyses and Specifications

3.1 Description of Variables

- $SDR_{C/E}$: SDR values are expressed in % and calculated at the midpoint of switching decisions and their preceding decision: For positive stated discount rates, the early period benefit (or addition) B_{early} at the switching point is saved as high-end value $B_{early}^{high-end}$ and the early period benefit of the preceding decision is saved as low-end value $B_{early}^{low-end}$. The SDR is then defined as: $SDR = \frac{1}{20} \ln \left(\frac{10}{\left(B_{early}^{low-end} + B_{early}^{high-end}\right)/2} \right)$. For negative discount rates, the benefit at the switching point is the low-end value and the benefit of the preceding decision is the high-end value. Analogously, negative stated discount rates are then defined as: $SDR = \frac{1}{20} \ln \left(\frac{\left(B_{later}^{low-end} + B_{later}^{high-end}\right)/2}{10} \right)$. For participants who choose the early benefit in the very first decision or the late benefit in the very last decision, we use the exact values and do not impute midpoints, as there is no preceding or succeeding decision.

- g_C/g_E: Growth rates are expressed in % and are continuous variables, rounded to two decimals, ranging from absolute values of 0.1 to 5.0. They are randomly drawn (uniformly) before participants start the experiment and are randomized between but not within participants and chosen separately for positive and negative growth rates. This means that participants are always confronted with the same positive growth rates per good and the same negative growth rates per good. We do this to create matching pairs of growth rates between the two scenarios, which allows us to compare the differences in the social discount rates in the context of the RPC equation.

3.2 General Specifications

- Exclusions: We exclude participants from our analyzes who completed the experiment in less than 15 minutes (fast clickers). Similarly, we exclude participants who failed one or more of the three attention checks in the survey. We also include rationality checks in our decision blocks: In the first (last) decision of each decision block we ask participants to trade-off a microscopic benefit earlier (later) against a multiple magnitudes larger benefit later (earlier). If they opt for the microscopic benefit in one of the two choices, we assume that they did not understand the trade-off at hand and exclude the corresponding decision block from the analysis.

- Standard errors: We utilize Huber–White robust standard errors and cluster standard errors at the individual-level to account for plausibly correlated error terms.

- Controls: To reduce noise in the data, we use controls in our regressions that account for cognitive uncertainty and belief in the consequentiality of answers. These controls consist of:

  - Stated cognitive uncertainty:

    Continuous variable ranging from 0 to 1. After each decision block, participants are asked how certain they are about their choice and preference and use a slider to select a value from 0% to 100%. This is motivated by Enke et al. (2025) and used to mitigate concerns about differences in answers being driven by the (increasing) complexity of scenarios.

- Stated comprehension of scenarios:

  Discrete variable ranging from 1 to 10. We ask participants about their perceived comprehension of the hypothetical scenarios at the end of the survey.

- Stated overall comprehension:

  Dummy variable taking on values 0 and 1. We ask participants about their overall comprehension of the experiment at the end of the survey.

- Stated ability to focus:

  Discrete variable ranging from 1 to 10. At the end of the survey we ask participants about their perceived ability to stay focused during the study.

- Belief in consequentiality:

  Dummy variable taking on values 0 and 1. At the end of the survey we ask participants if they belief that their answers and the answers of other participants in the survey will be consequential.

• Statistical tests:

  $H_0^{7,a}$ is tested using a two-sample t-test to compare the means of the two distributions and $H_0^{7,b}$ is tested with a Brown-Forsythe test. For tests involving bootstrapped estimates, we similarly use a two-sided t-test. All other linear restrictions are assessed using a Wald test. We adjust the tests of the hypotheses 11-13 and the sub-hypotheses of 14 and 15 by the Holm-Bonferroni method because for these cases, a rejection of either (sub-)hypothesis is sufficient for an overall statement.

3.3 Models and Tests

We use the following OLS regression model as our main specification:

$$SDR_{C/E;i} = \delta + \eta_{CC} g_{CC;i} + \eta_{EE} g_{EE;i} + \eta_{CE} g_{CE;i} + \eta_{EC} g_{EC;i} + \mathbf{Z_i}\theta + \epsilon_i \tag{7}$$

The intercept of this regression equals the pure rate of time preference δ. The growth rate $g_{XY;i}$ denotes the growth for good Y in the scenario regarding good X and in decision block i, where $X, Y \in \{C, E\}$. The elasticities η_{XY} denote the marginal utility elasticity of good X with respect to good Y. The set of controls is denoted as $\mathbf{Z_i}$ and ϵ_i denotes the error term. This model allows testing hypotheses 1-3, 5, 6 and 11.

To test hypothesis 4, we add an additional regression term $\delta_{\Delta E} D_{E;i}$ where $D_{E;i}$ is a dummy variable that equals 1 in case the decision block i belongs to the non-market good environment scenario, and 0 otherwise, and identifies the pure rate of time preference δ_E as the difference $\delta_{\Delta E}$ to the consumption scenario pure rate of time preference δ_C which is the intercept of the regression[8].

To test hypothesis 7a we perform a simple two-sided t-test for the difference in means between the observed values $SDR_{C;i}$ and $SDR_{E;i}$. To test hypothesis 7b we use a Brown-Forsythe test which identifies systematic differences in the variances of the two distributions.

Hypothesis 8 is tested through the following OLS regression model of the RPC equation, where $\sigma = \frac{1}{\beta_\sigma}$:

$$\Delta SDR_i = \beta_\sigma (g_{C;i} - g_{E;i}) + \mathbf{Z_i}\theta + \epsilon_i$$

To obtain observations of ΔSDR_i, $g_{C;i}$ and $g_{E;i}$ we create matching pairs of decision blocks across the two scenarios, such that we observe both $SDR_{C;i}$ and $SDR_{E;i}$ at the same time, for a pair of growth rates $g_{C;i}$ and $g_{E;i}$. As described in 3.1, we facilitate this by varying

[8]Essentially, $D_{E;i}$ returns 1 for each decision block in the environment scenario that involves timing trade-offs; The difference in the pure rate of time preference is then identified through the first decision block that only involves a timing trade-off.

growth rates across but not within individuals, allowing us to match each decision block of the consumption scenario to a corresponding decision block of the environment scenario for each participant.

To test hypotheses 9 and 10, note that we can then express the equation for the consumption discount rate in the CES-CIES model as $SDR_C = \delta + \theta_1 g_C + \theta_2 g_E$ with $\theta_1 = \frac{1}{\gamma}\lambda + \frac{1}{\sigma}(1-\lambda)$ and $\theta_2 = (1-\lambda)(\frac{1}{\gamma} - \frac{1}{\sigma})$, such that $\gamma = \frac{1}{\theta_1+\theta_2}$ and $\lambda = 1 - \frac{\theta_2}{\frac{1}{\gamma}-\frac{1}{\sigma}}$. As the equation for SDR_C here is equivalent to our initial dual discounting model, θ_1 and θ_2 are also equivalent to our main regression estimates η_{CC} and η_{CE} and we can simply use the estimates from our main regression model to impute the estimates for γ and λ directly. To assess goodness-of-fit we bootstrap the corresponding standard errors by resampling the estimates 1,000 times. We repeat this procedure analogously for the environment discount rate SDR_E in the CES-CIES model to gather two distinct pairs of estimates γ_C, λ_C and γ_E, λ_E of the same underlying parameters, which allows us to test the internal consistency hypotheses 12 and 13.

Hypothesis 14 is then tested by using the following polynomial specification of the RPC equation above, where, as before, $\sigma_x = \frac{1}{\beta_{\sigma_x}}$:

$$\Delta SDR_i = \beta_{\sigma_C} g_{C;i} + \beta_{\sigma_{C;2}} g_{C;i}^2 - \beta_{\sigma_E} g_{E;i} - \beta_{\sigma_{E;2}} g_{E;i}^2 + \mathbf{Z_i}\theta + \epsilon_i$$

For the hypotheses 16-18 that investigate the heterogeneity in growth rates we utilize Eq. (7) and split the terms accordingly. For example, hypothesis 16 is then tested using the following equation:

$$SDR_{C/E;i} = \delta + \sum_{X\in\{C,E\}} \sum_{s\in\{p,n\}} \eta_{XX}^{X_s} g_{XX;i}^{s} + \eta_{CE} g_{CE;i} + \eta_{EC} g_{EC;i} + \mathbf{Z}_i\theta + \epsilon_i \qquad (8)$$

As a test of whether elasticities are constant, i.e. for assessing hypotheses 15 and 19, we use the following OLS regression model that extends our main regression by quadratic growth terms:

$$SDR_{C/E;i} = \delta + \sum_{XY \in \{CC,EE,CE,EC\}} \left(\eta_{XY}\, g_{XY;i} + \eta_{XY;2}\, g^2_{XY;i}\right) + \mathbf{Z_i}\theta + \epsilon_i \tag{9}$$

Finally, to test hypothesis 20 we include the good-specific pure rate of time preference term $\delta_E D_{E;i}$ and split the independent variables analogously and arrive at the following extended version of our main OLS regression model:

$$SDR_{C/E;i} = \delta_C + \sum_{d \in \{\text{Forest,AirQuality}\}} \left(\delta^d_E\, D^d_{E;i} + \sum_{X,Y \in \{C,E\}} \eta^d_{XY}\, g^d_{XY;i}\right) + \mathbf{Z}_i\theta + \epsilon_i \tag{10}$$

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