Complementarity Preferences

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Motivation

Limited substitutability of nature is a key issue for sustainable development (Heal 1998, Neumayer 2013, Traeger 2010 *JEEM*, Gollier 2019 *JEEM*, Zhu et al. 2019 *JEEM*, ...).

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It determines:

- Resilience or fragility of nature-dependent economies
  (e.g., Quaas et al. 2013 *JEEM*; Giglio et al. 2025)
- Higher SCC (Sterner&Persson 2008 *REEP*; Drupp&Hänsel 2021 *AEJ:Policy*)
- Increased benefits from scarce ecosystems in CBA (e.g., Drupp et al. 2024 *Science*), largest for biodiversity due to strong decline (NPV increases >1200% over 100yrs)
- ...

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Challenges:

1. Empirical evidence on limited substitutability in utility relies solely on indirect estimation via the income elasticity of WTP
2. Theory and empirics have relied on assuming equal preference elasticities

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   $\Rightarrow$ Relevant i.a. for comprehensively accounting for the value of environmental goods in decision-making and accounting (Aichi Target 2, Convention on Biological Diversity)

1. Simple(st) WTP model

- Continuum of individuals that differ in their CES preferences for limited substitutabilit/ complementarity of an environmental public good, E, vis-a-vis a private market good, C

$$U_i(C, E; \eta_i) = \left(\alpha C^{1-\eta_i} + (1-\alpha)\, E^{1-\eta_i}\right)^{\frac{1}{1-\eta_i}}. \tag{1}$$

  - $\alpha \in (0, 1)$ is the utility share of the private good, and
  - $\eta_i \in \mathbb{R}$ is individual i's inverse of the elasticity of substitution between the public good and the private good ("elasticity of complementarity"), which equals the income elasticity of WTP (see, e.g., Ebert 2003 *EARE*; Baumgärtner et al. 2017 *JEEM*)

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- Consider a single, numeraire market consumption good ($P = 1$), thus $C = Y$.

- Individual marginal willingness to pay (WTP) for one unit of E is given by:

$$\omega_i(Y, E; \eta_i) \;:=\; \frac{\partial U_i(\frac{Y}{P}, E; \eta_i)/\partial E}{\partial U_i(\frac{Y}{P}, E; \eta_i)/\partial Y} \overset{(2)}{=} \frac{1-\alpha}{\alpha} \left(\frac{Y}{E}\right)^{\eta_i}. \tag{3}$$

(note that this is a first-order approximation of WTP, see Smith 2023 *JEEM*).

1. Simple(st) WTP model

- Consider η as a distributed variable that describes the continuous distribution of the elasticity of complementarity in the population.

- Derive mean marginal WTP as the expected value for a given distribution of η:

$$\overline{\omega}(Y, E; \eta) := \mathbb{E}_\eta \left[\omega(Y, E; \eta)\right] \overset{(3)}{=} \mathbb{E}_\eta \left[\frac{1-\alpha}{\alpha} \left(\frac{Y}{E}\right)^\eta\right] = \frac{1-\alpha}{\alpha} \mathbb{E}_\eta \left[\left(\frac{Y}{E}\right)^\eta\right]. \tag{4}$$

2. Results: Mean-preserving spread in η increases mean WTP

- Mean marginal WTP is the expected value for a given distribution of η:

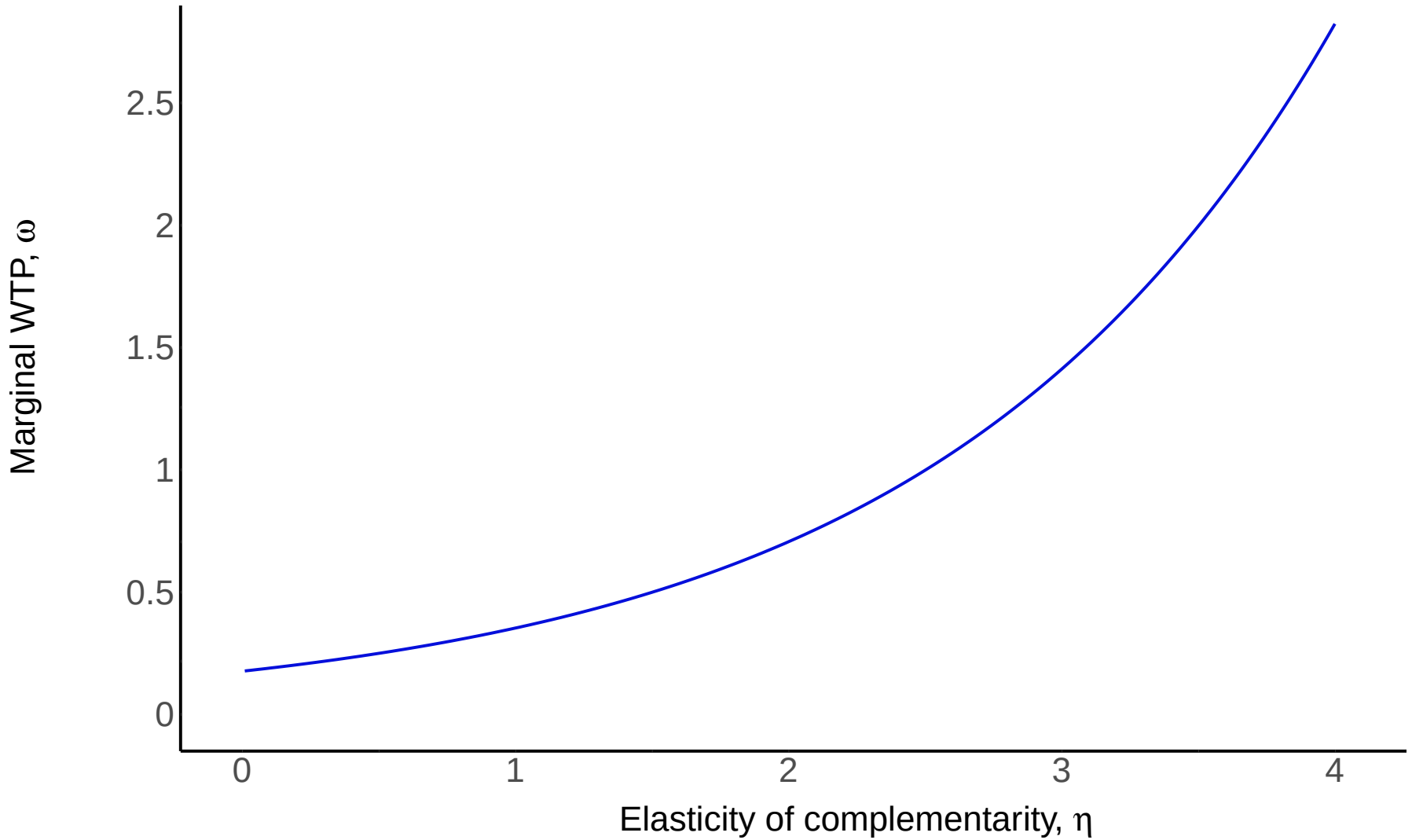
$$\overline{\omega}(Y, E; \eta) := \mathbb{E}_\eta \left[\omega(Y, E; \eta)\right] \overset{(3)}{=} \mathbb{E}_\eta \left[\frac{1-\alpha}{\alpha} \left(\frac{Y}{E}\right)^\eta\right] = \frac{1-\alpha}{\alpha} \mathbb{E}_\eta \left[\left(\frac{Y}{E}\right)^\eta\right]. \tag{5}$$

Proposition 1. *Any mean preserving spread in η, i.e. complementaroty preference heterogeneity, increases the economic value of the environmental public good. The only exception is the case where the levels of market and non-market goods are identical.*

Proof by Jensen's inequality.

2. Results: Mean-preserving spread in η increases mean WTP

Prop. 1: A mean preserving spread in complementarity preferences increases mean WTP.



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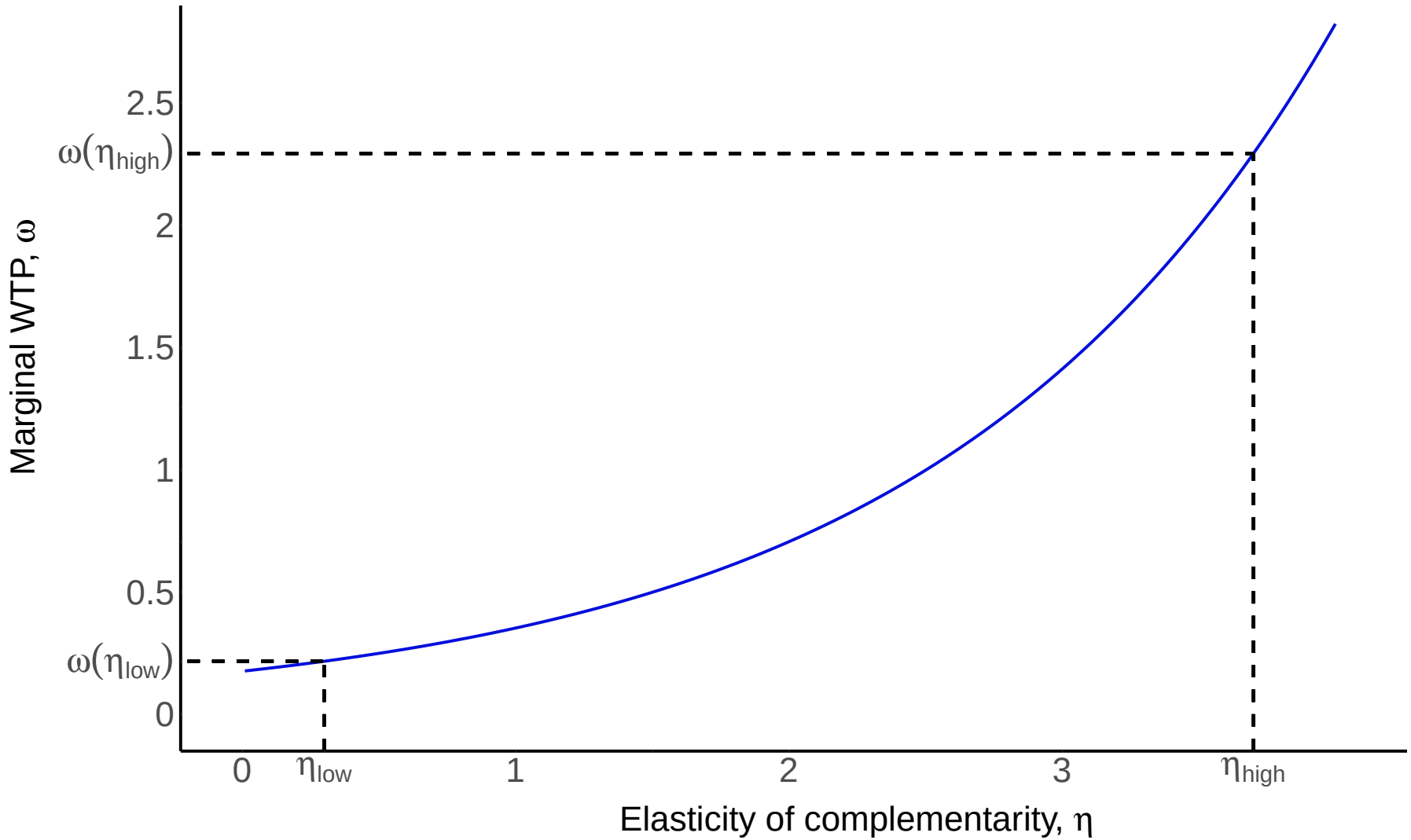

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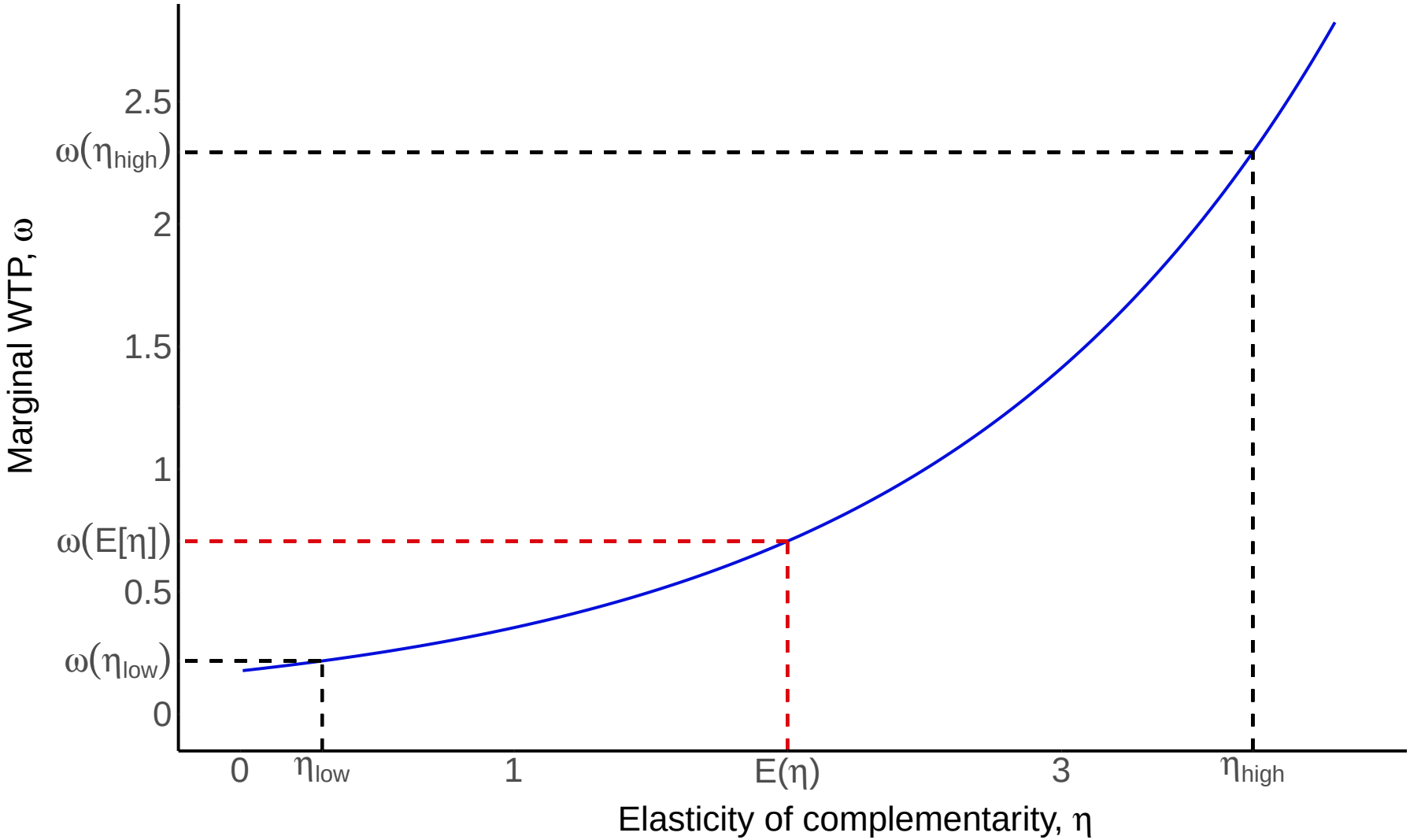

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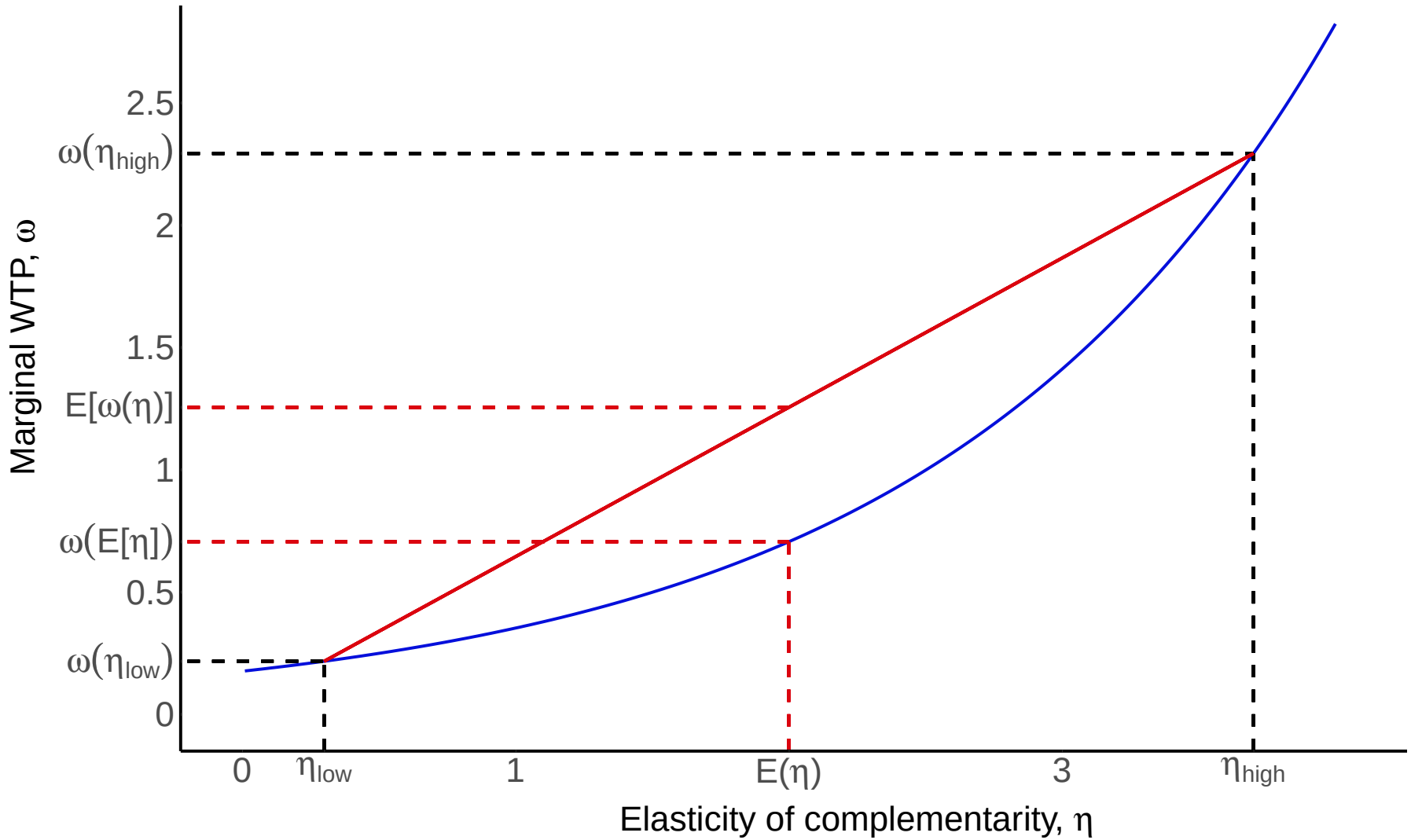

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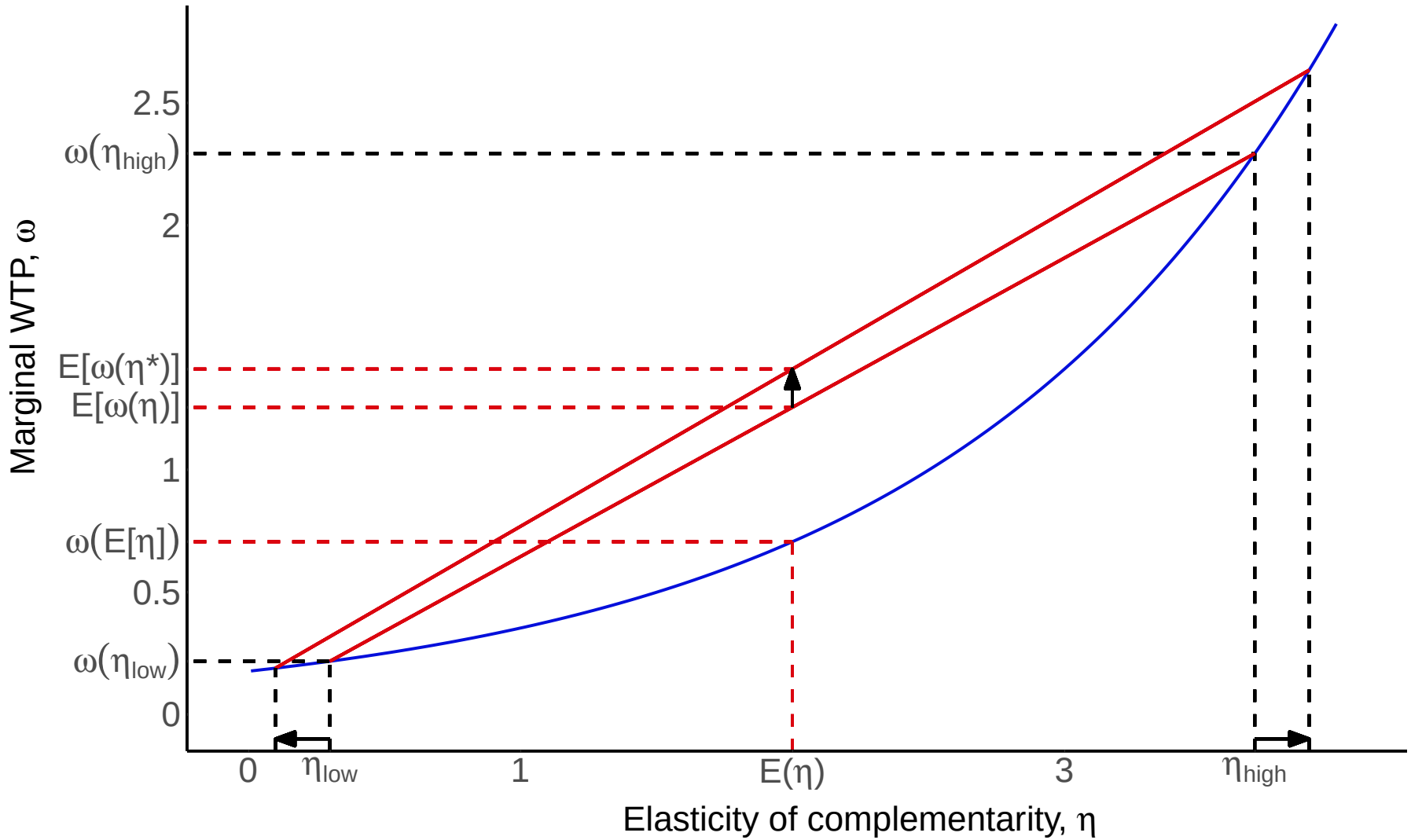

3. Generalizing results with moment generating functions

Using a moment generating function approach, we can derive how mean WTP depends more generally on the distribution of complementarity preferences and its cumulants/moments:

$$\overline{\omega}(Y, E; \eta) = \frac{1-\alpha}{\alpha} \exp\left(\sum_{k=1}^{\infty} \frac{\kappa_k}{k!} \left(\ln\left(\frac{Y}{E}\right)\right)^k\right) . \tag{6}$$

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Cumulants (κ_k)	**Moments**	**Comparative statics**
κ_1 (Mean μ)	$\mu_\eta = \mathbb{E}[\eta]$	$\ln\left(\frac{Y}{E}\right) \gtreqless 0 \iff Y \gtreqless E$
κ_2 (Variance σ^2)	$\sigma_\eta^2 = \mathrm{Var}[\eta]$	$\frac{1}{2}\left(\ln\left(\frac{Y}{E}\right)\right)^2 \geq 0$
κ_3 (Skewness)	$\mathbb{E}[(\eta-\mu)^3]$	$\frac{1}{6}\left(\ln\left(\frac{Y}{E}\right)\right)^3 \gtreqless 0 \iff Y \gtreqless E$
κ_4 (Excess Kurtosis)	$\mathbb{E}[(\eta-\mu)^4] - 3\sigma_\eta^4$	$\frac{1}{24}\left(\ln\left(\frac{Y}{E}\right)\right)^4 \geq 0$
...		

$\Rightarrow$ Mean marginal WTP increases in even cumulants (beyond the variance).

$\Rightarrow$ Mean marginal WTP increases (decreases) in odd cumulants if $Y > E$ ($Y < E$)

4. Heterogeneity statistics

We can also compare mean marginal WTP under heterogeneous preferences to the standard case of homogeneous preferences and derive a factor to capture by how much preference heterogeneity increases mean WTP.

Heterogeneity factor:

$$h(K_\eta) = \exp\left[K_\eta\left(\ln\left(\frac{Y}{E}\right)\right) - \mu_\eta \ln\left(\frac{Y}{E}\right)\right]. \tag{8}$$

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Alternatively, we can ask how high the mean elasticity with homogeneous preferences needs to be to give the same mean marginal WTP as in a situation with preference heterogeneity. This heterogeneity equivalent, μ_η^*, is implicitly defined as $\overline{\omega}(\mu_\eta^*, 0) = \overline{\omega}(K_\eta)$.

Heterogeneity equivalent:

$$\mu_\eta^* = \frac{K_\eta\left(\ln\left(\frac{Y}{E}\right)\right)}{\ln\left(\frac{Y}{E}\right)}. \tag{10}$$

4. Special cases that can feature existing, closed-form MGF/CGF

1. Normal distribution: is always symmetric, defined only by its first two cumulants:

$$\overline{\omega}_N(Y, E; \eta) = \frac{1-\alpha}{\alpha} \exp\left(\mu_\eta \ln\left(\frac{Y}{E}\right) + \frac{\sigma_\eta^2}{2}\left(\ln\left(\frac{Y}{E}\right)\right)^2\right) \tag{11}$$

- Considered by Gollier (2019 *JEEM*) to study how preference *uncertainty* affects ecological discounting and the value of natural capital

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- Here, the **heterogeneity factor** is given by

$$h_N(\sigma_\eta) := \frac{\overline{\omega}(\mu_\eta, \sigma_\eta^2)}{\overline{\omega}(\mu_\eta, 0)} = \exp\left[\frac{\sigma_\eta^2}{2} \ln\left(\frac{Y}{E}\right)^2\right]. \tag{13}$$

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2. Gamma distribution: is inherently skewed ($\kappa_3 > 0$) and leptokurtic ($\kappa_4 > 0$), with shape s, scale θ and an existing CGF if $\theta \ln(Y/E) < 1$:

$$\overline{\omega}_\Gamma(Y, E; \eta) = \frac{1-\alpha}{\alpha}\left(1 - \theta \ln\left(\frac{Y}{E}\right)\right)^{-s} \tag{16}$$

$\Rightarrow$ The Gamma **heterogeneity factor**, $h_\Gamma(\sigma_\eta)$, increases more than exponentially

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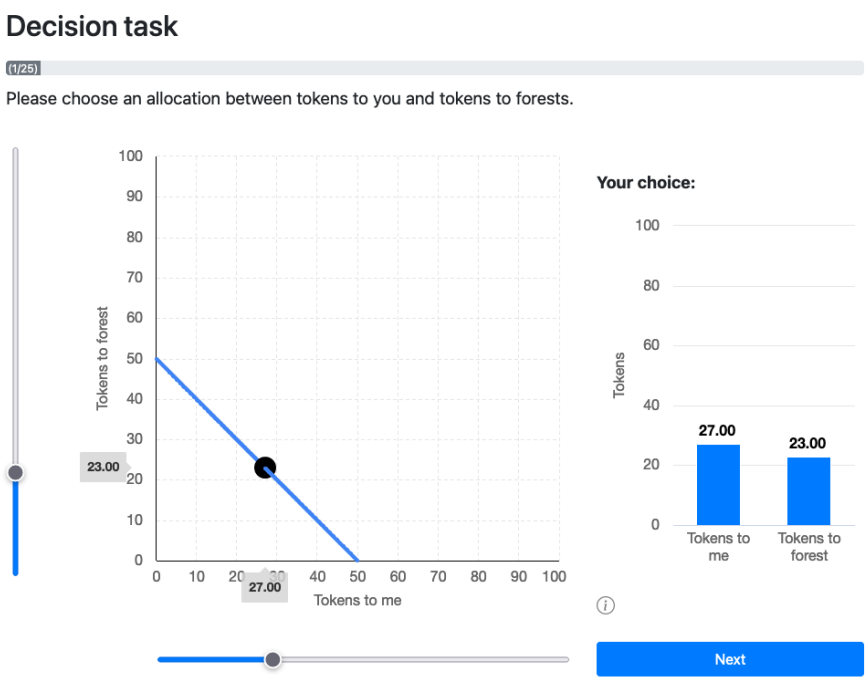

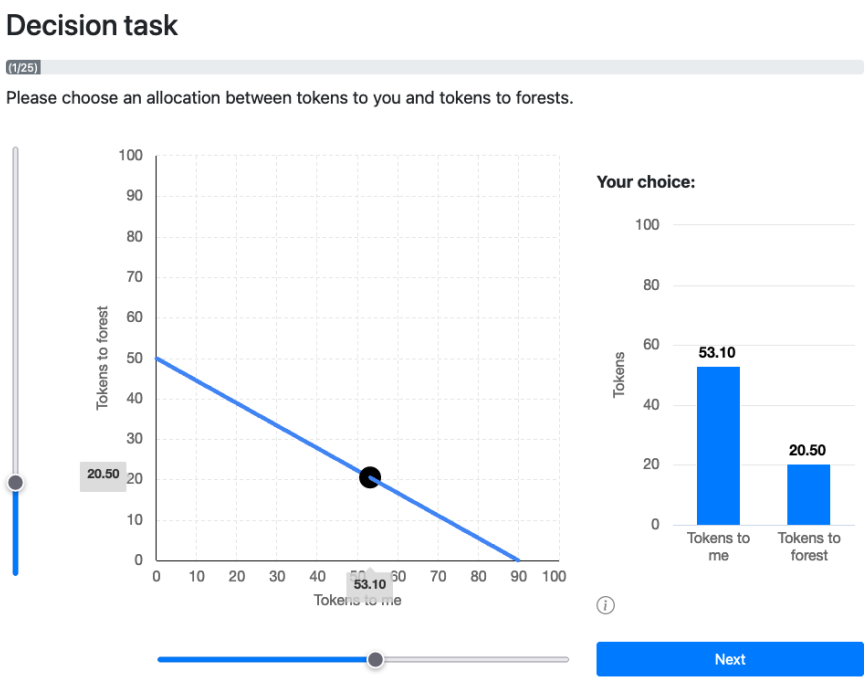

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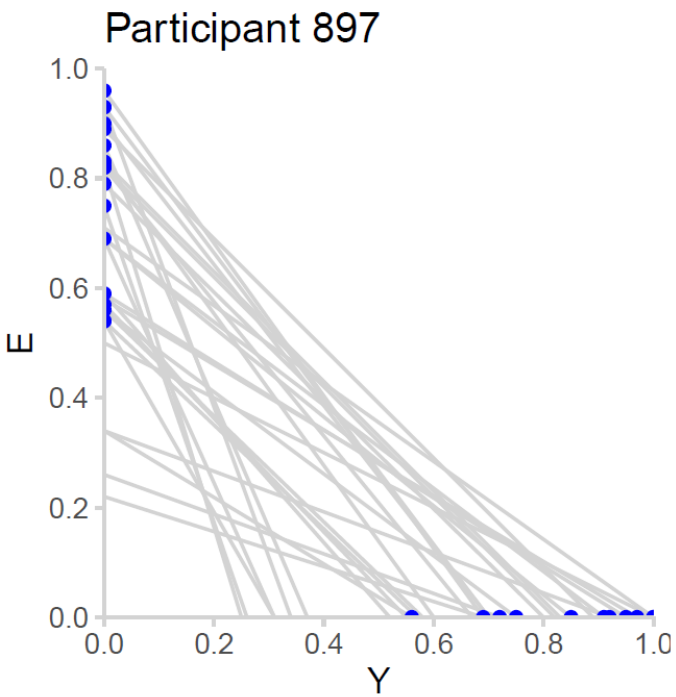
- Subjects choose between keeping part of a budget to themselves and giving it to planting trees (German state forestry), 30 times repeatedly at varying prices of giving and budgets
- Estimate CES preferences (α_i and η_i) using non-linear two-limit tobit MLE
  - Real effective price variation of tree-planting is achieved via matching
  - 4 treatments: Individual / Public; Hypothetical / Incentivized

  $\Rightarrow \approx$1500 respondents, online representative sample from Germany

Archetypal Preferences I



Raw choices

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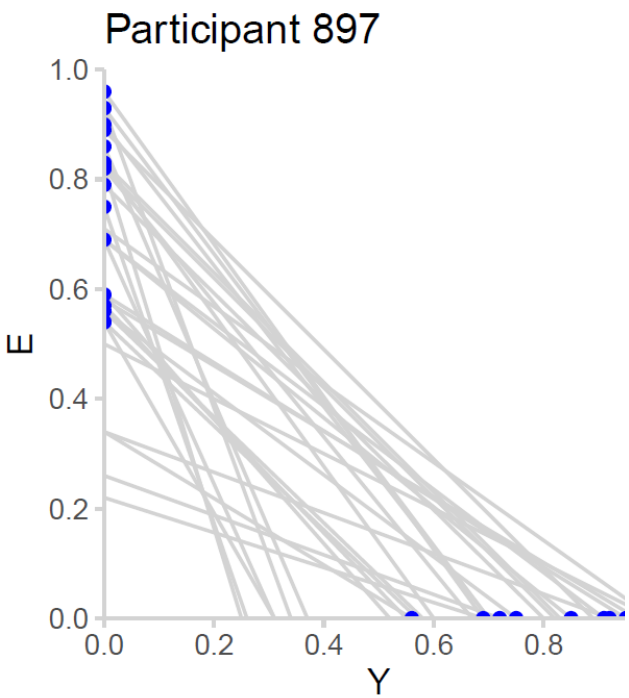

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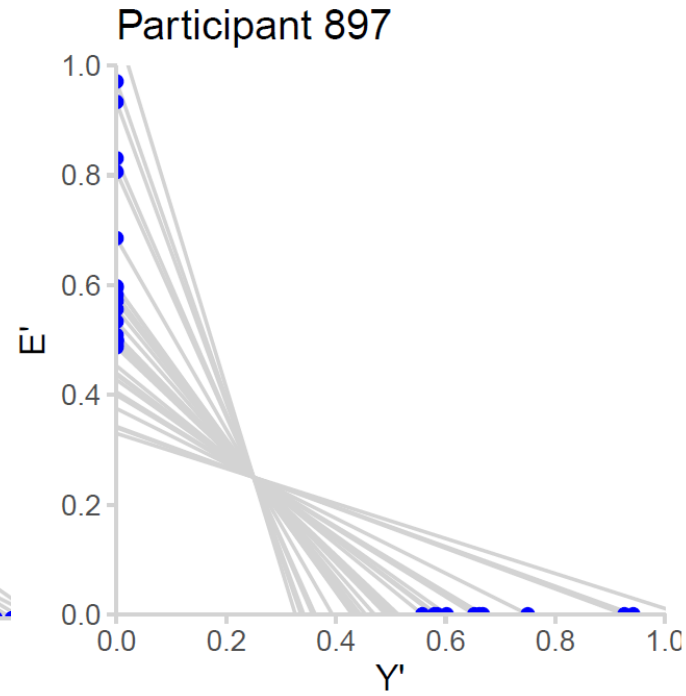
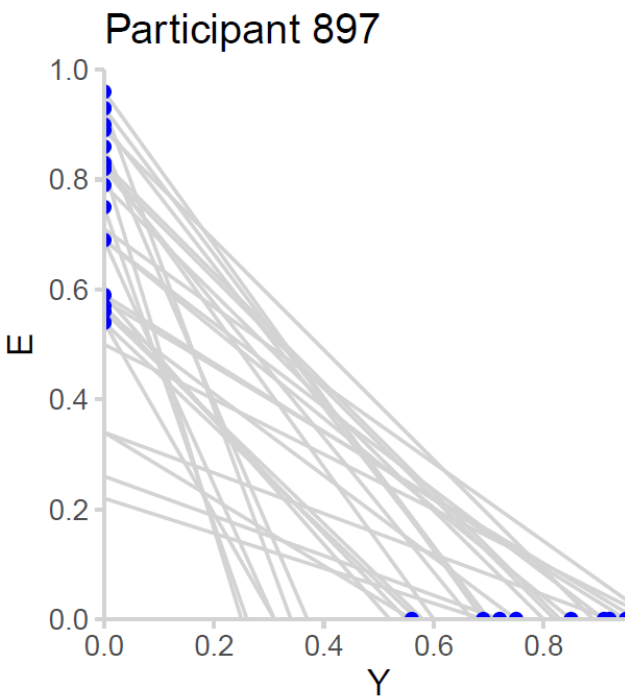
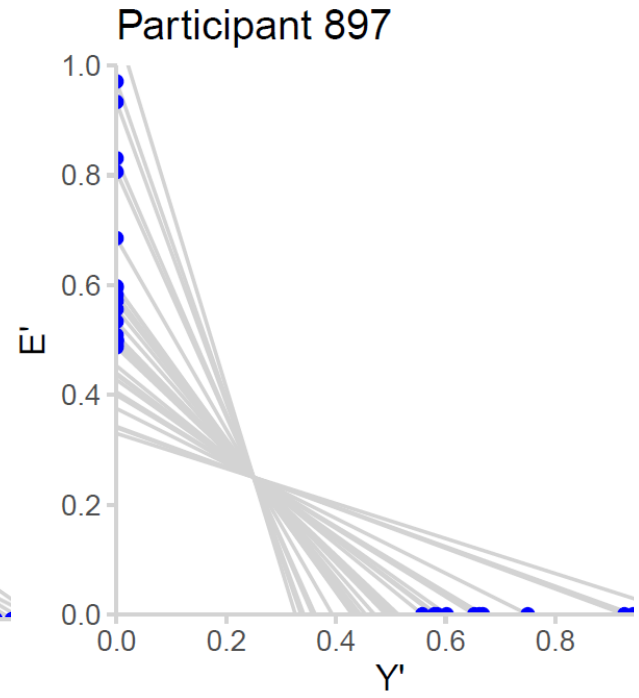
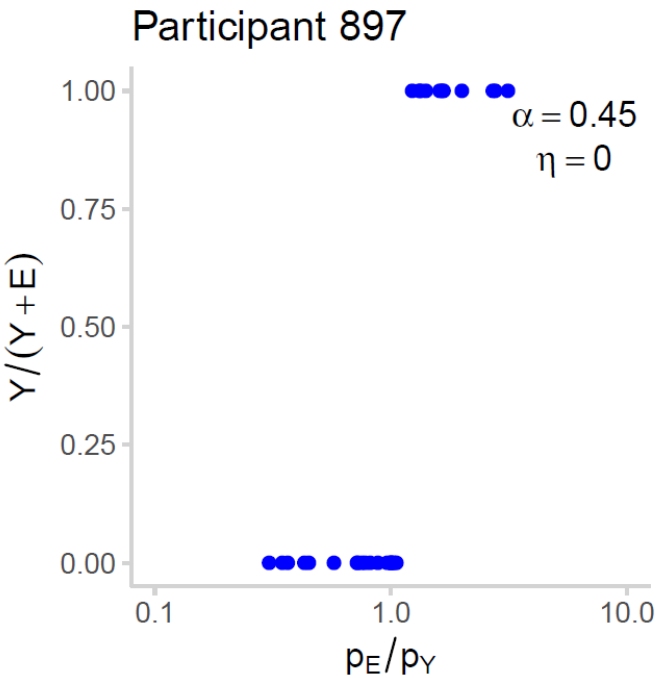


Harmonized budgets

Archetypal Preferences I







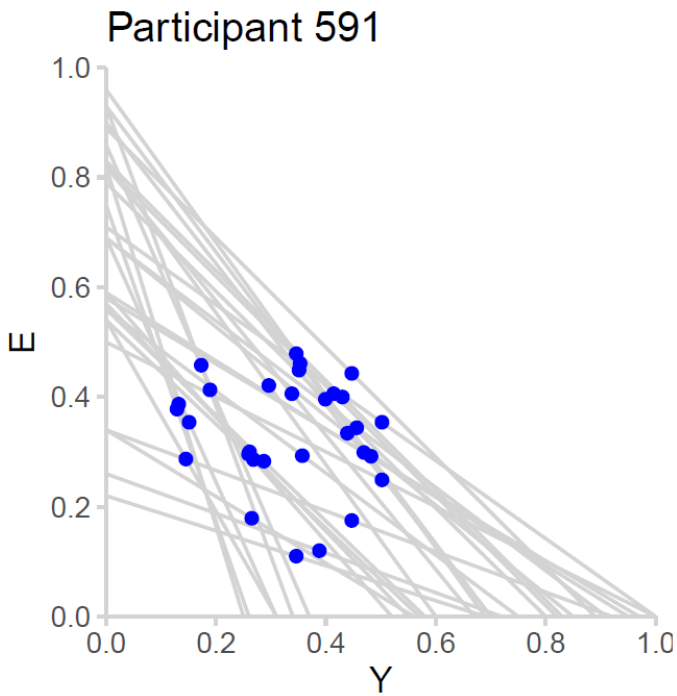
Raw choices

Harmonized budgets

Choices along relative prices

$\Rightarrow$ **Perfect substitutability**

Archetypal Preferences II



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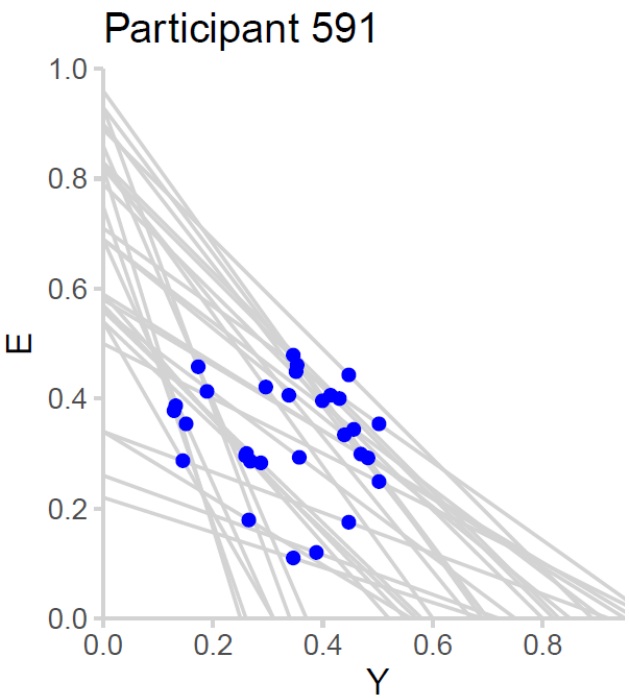

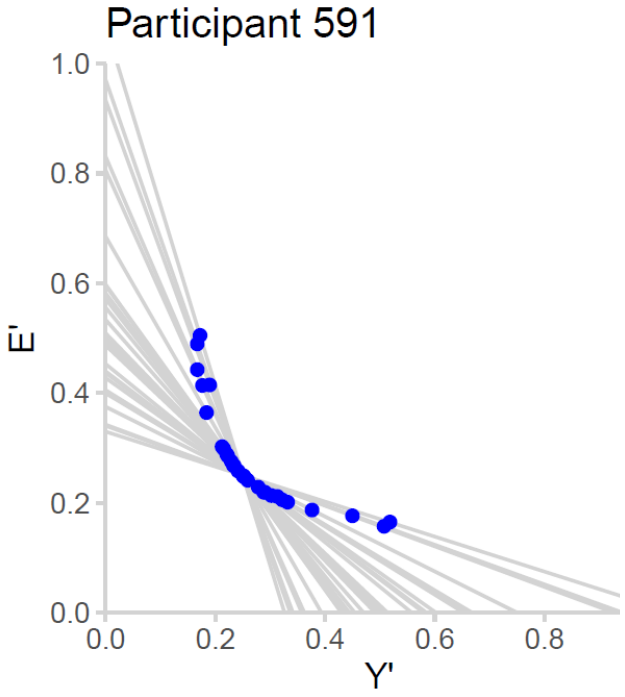

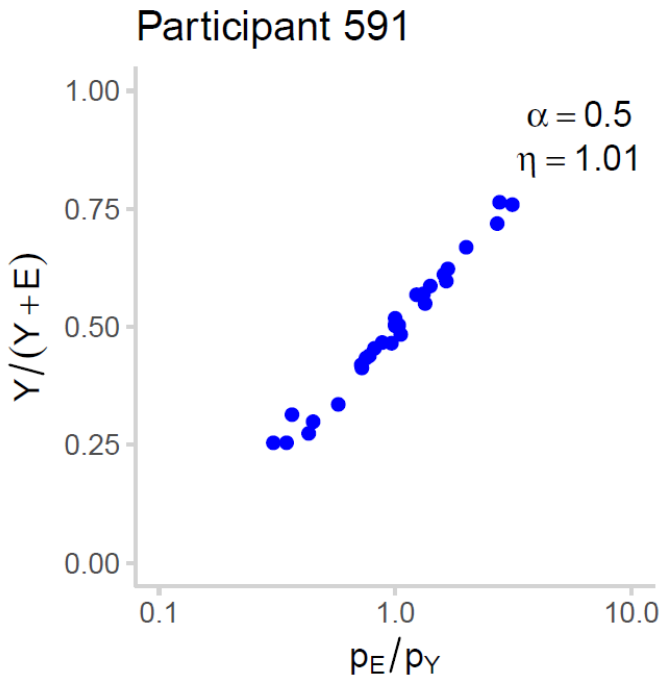

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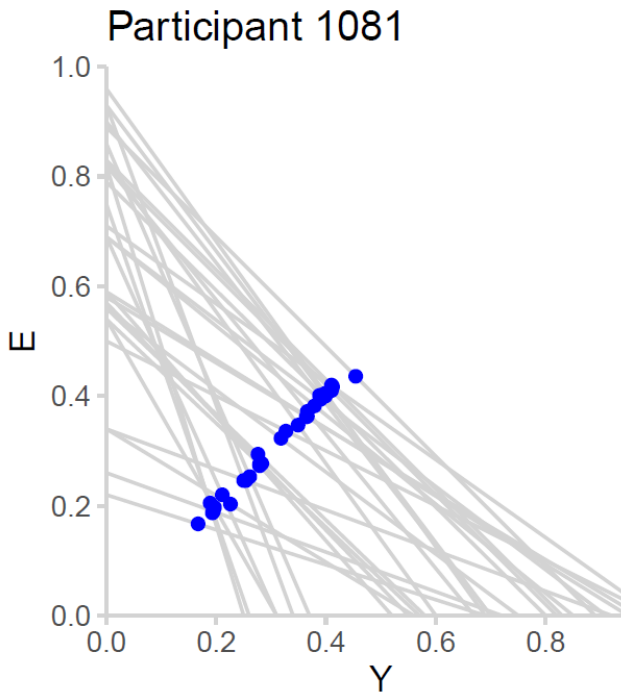
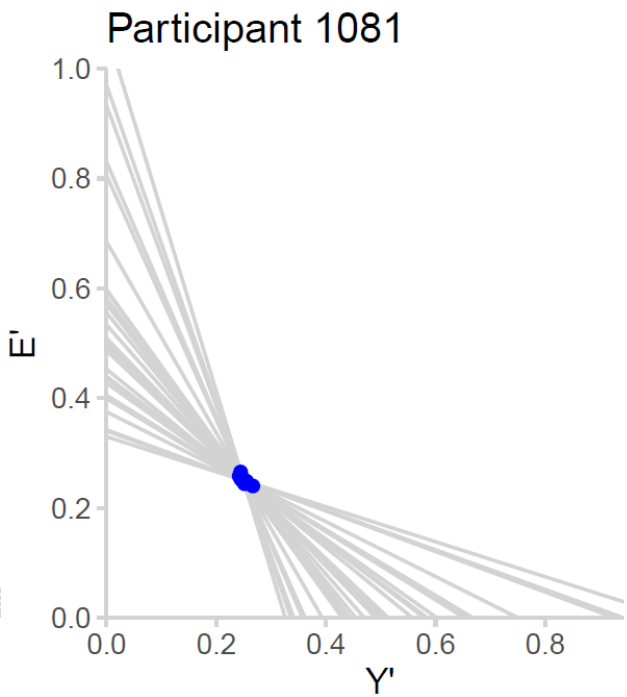
Harmonized budgets

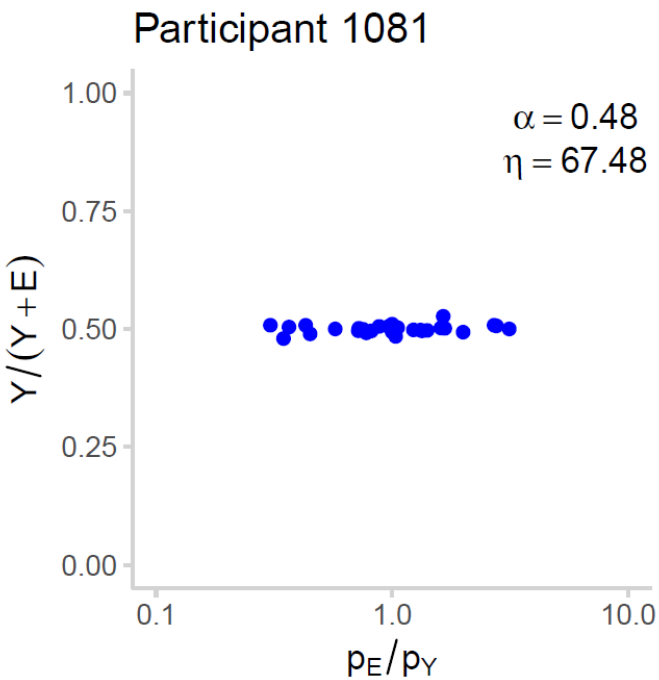
Choices along relative prices

$\Rightarrow \approx$ **Cobb-Douglas**

Archetypal Preferences III



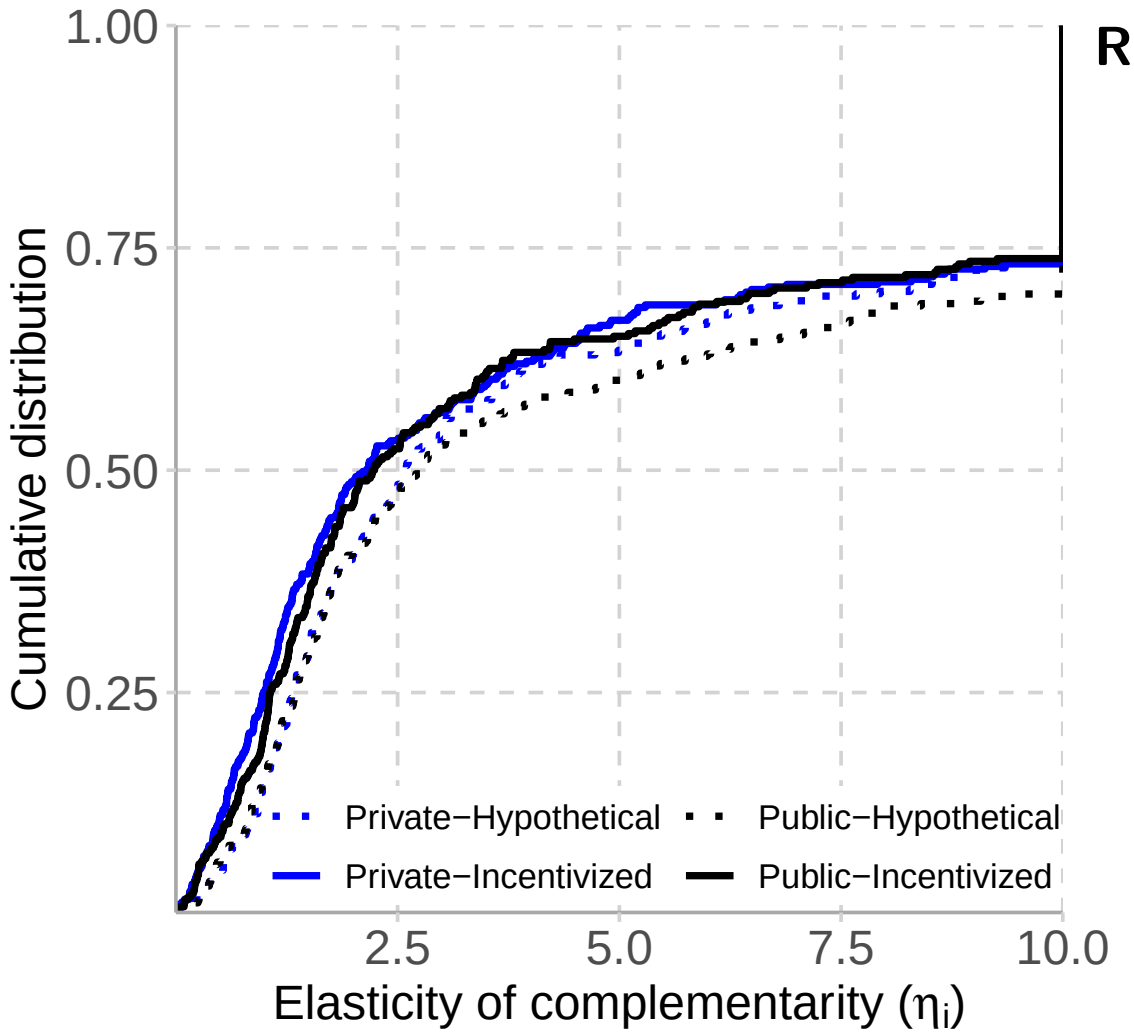




$\Rightarrow \approx$ **Perfect complementarity**

6. Empirical distribution of the elasticity of complementarity, η

A



R1: Complementarity preferences are similar across treatments (but α larger in Private settings)

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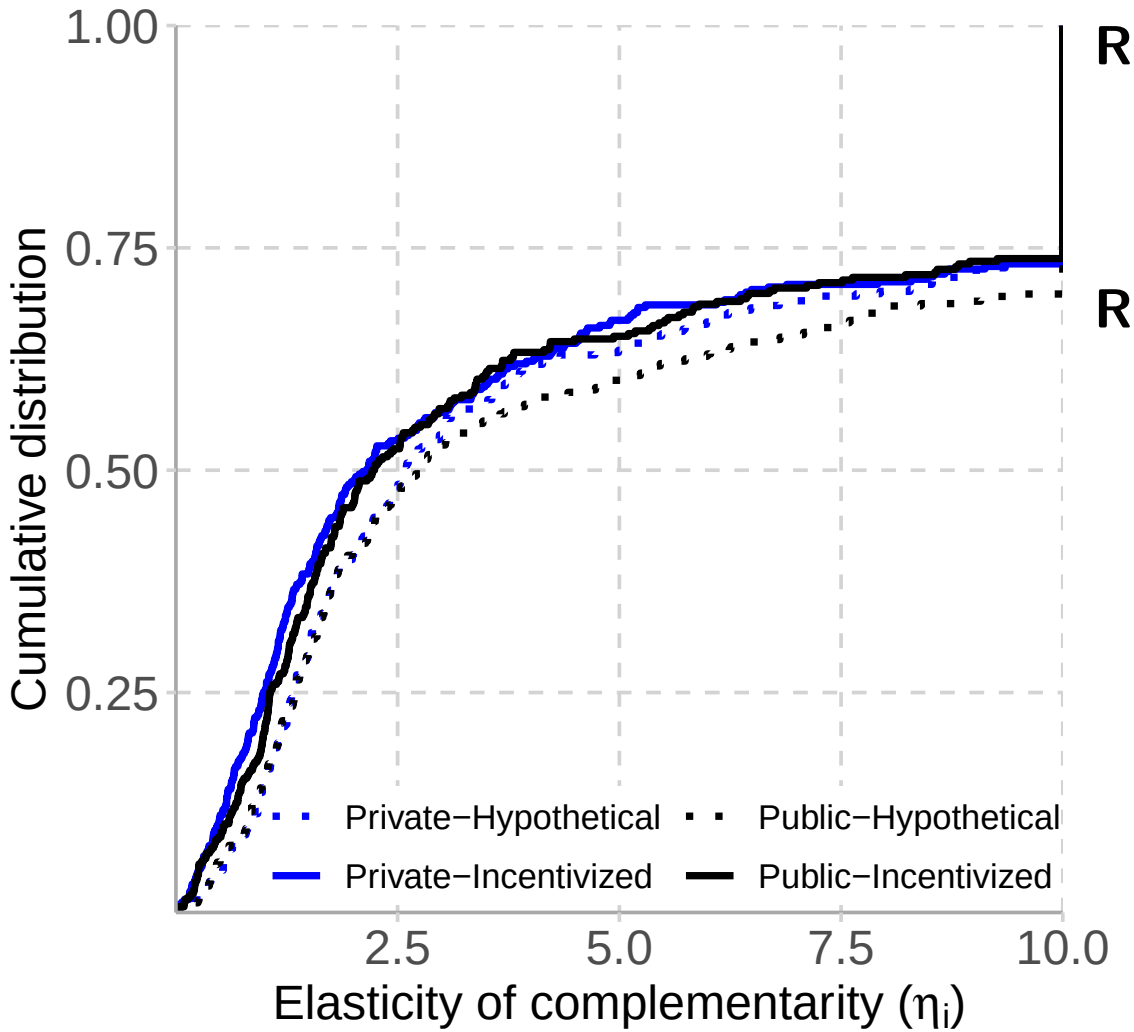

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- Median$\approx$2.5, close to value used in Sterner&Persson (2008)

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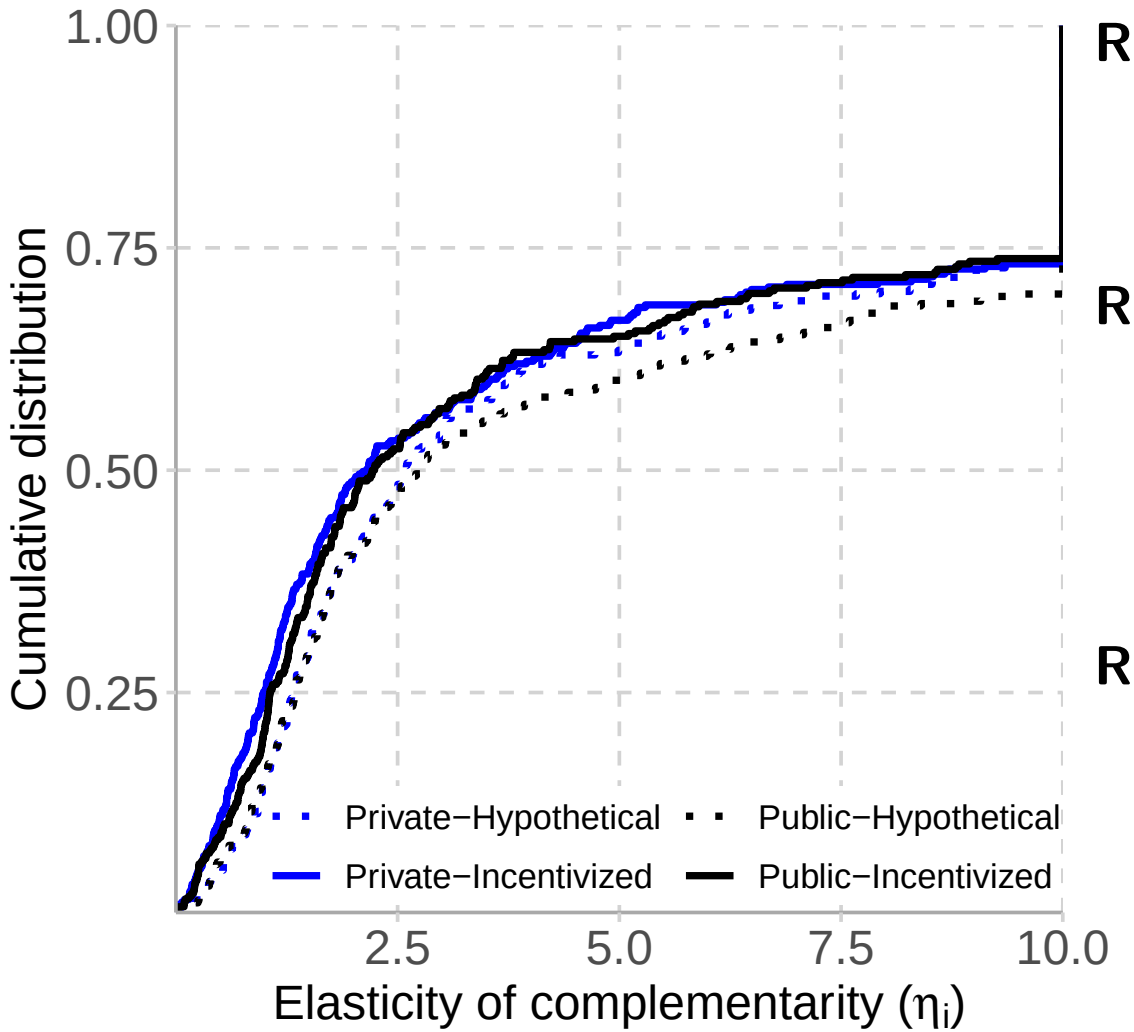

R1: Complementarity preferences are similar across treatments (but α larger in Private settings)

R2: The vast majority of preferences are in the complementarity domain

- Median≈2.5, close to value used in Sterner&Persson (2008)

R3: The heterogeneity of complementarity preferences is substantial

- Distribution (very) heavy tailed

7. Illustration of theoretical results

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To illustrate our theoretical results, we consider

- Mean/median of utility share parameter, $\alpha = 0.47$
- Truncated distribution of $\eta_i \leq 50$ to allow for the CGF of the Gamma distribution to exist (mean: $\mu_\eta = 6$, variance: $\sigma^2_\eta \approx$90, MLE fit for Gamma distribution: $\sigma^2 = 54$)
- Illustrative goods ratio of $Y/E = 1.1$

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We then compute mean marginal WTPs for

1. **Normal distribution**, $\overline{\omega}_N(\mu_\eta, \sigma^2_\eta)$
2. **Gamma distribution** $\overline{\omega}_\Gamma(\theta, s)$
3. **Flexible empirical distribution**, $\overline{\omega_i}(Y, E; \eta_i)$

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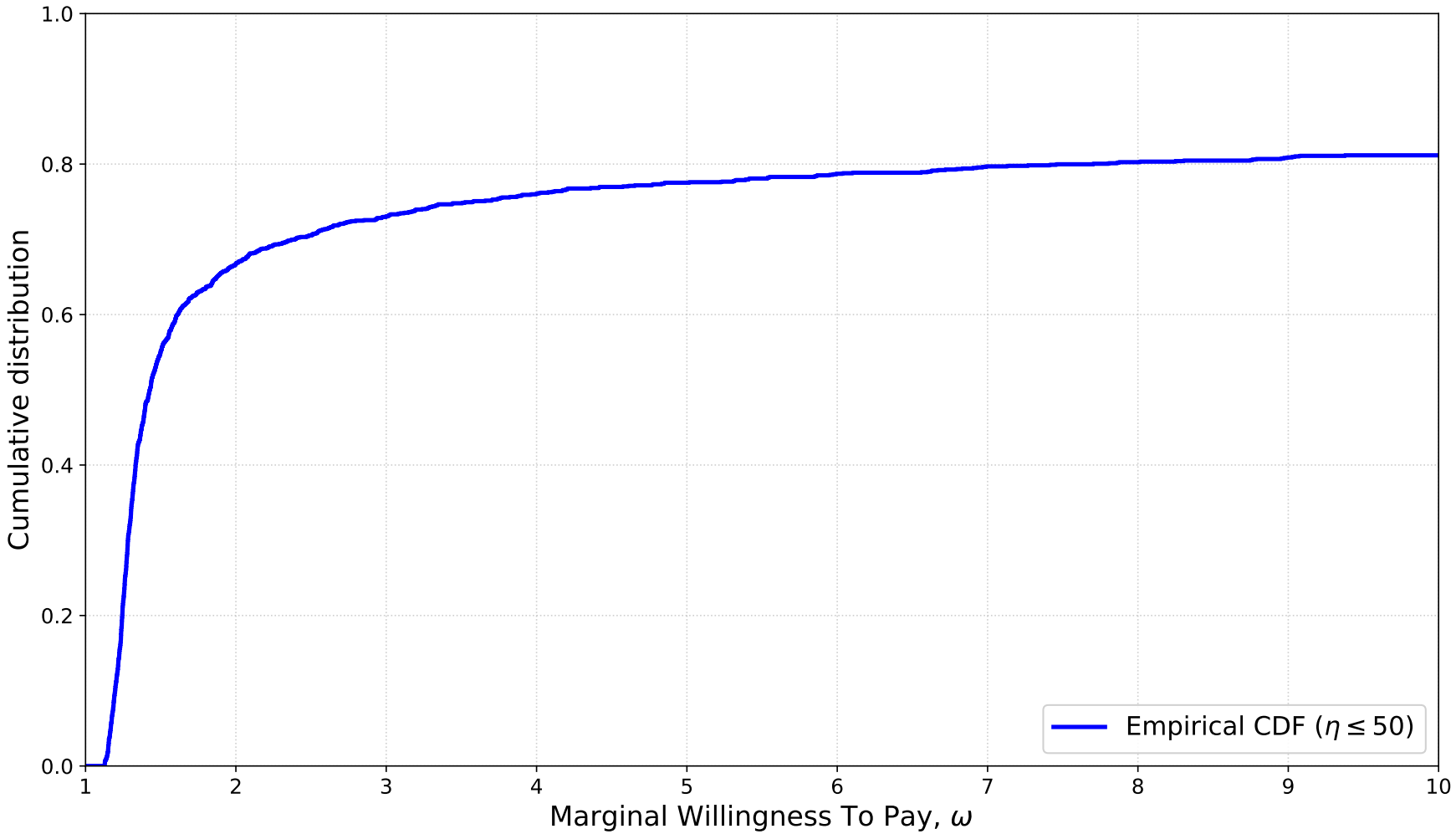

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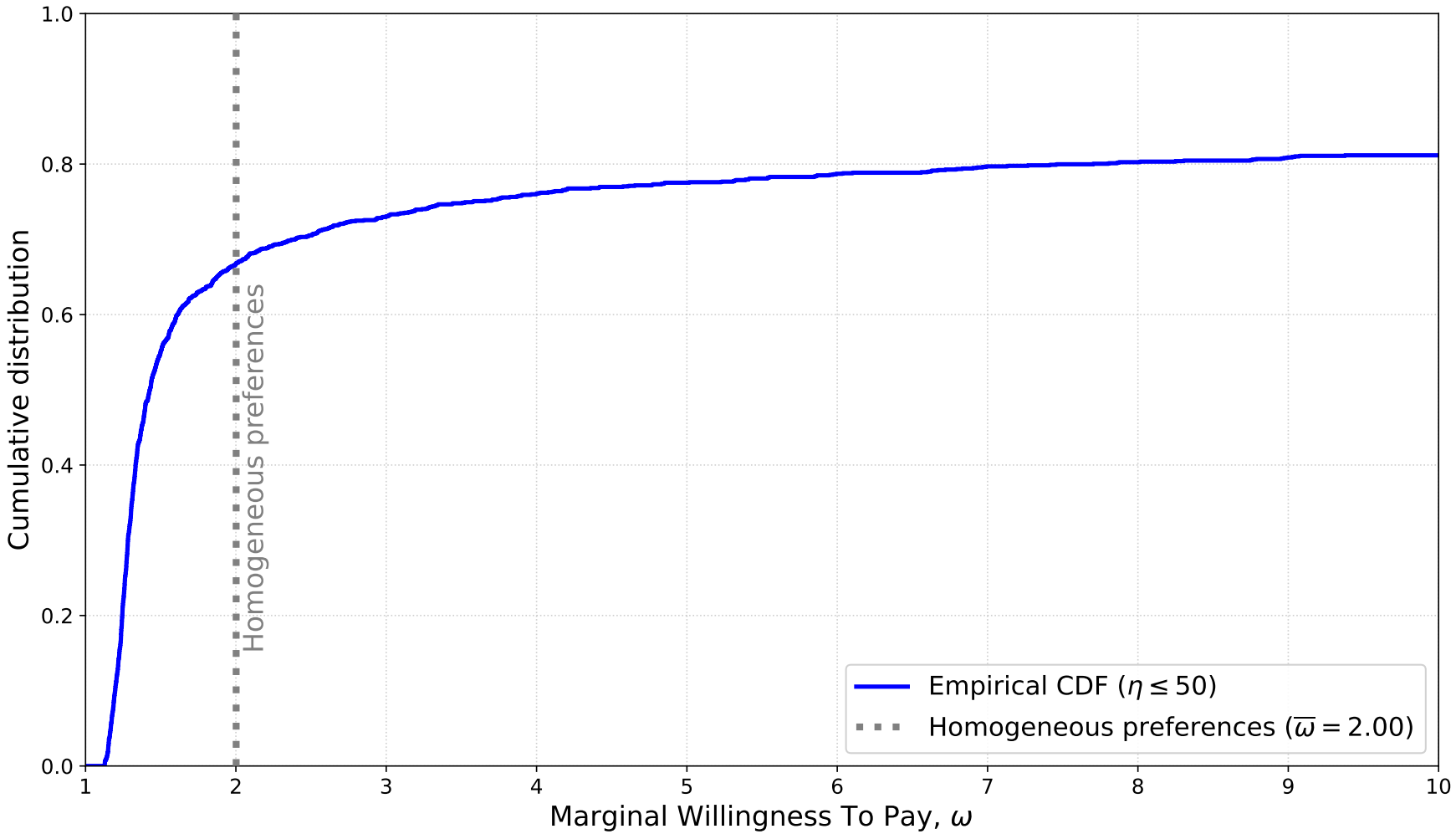

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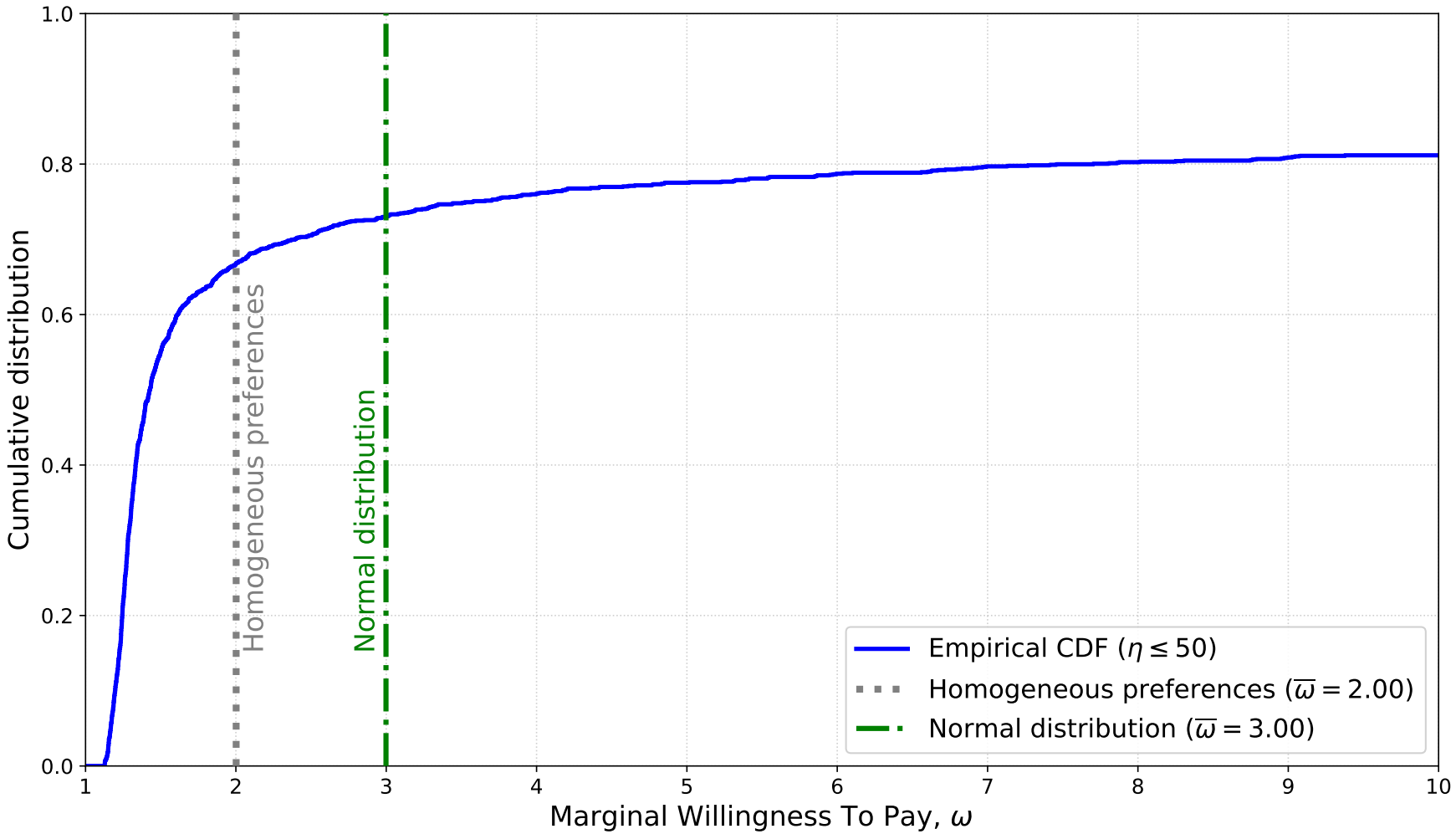

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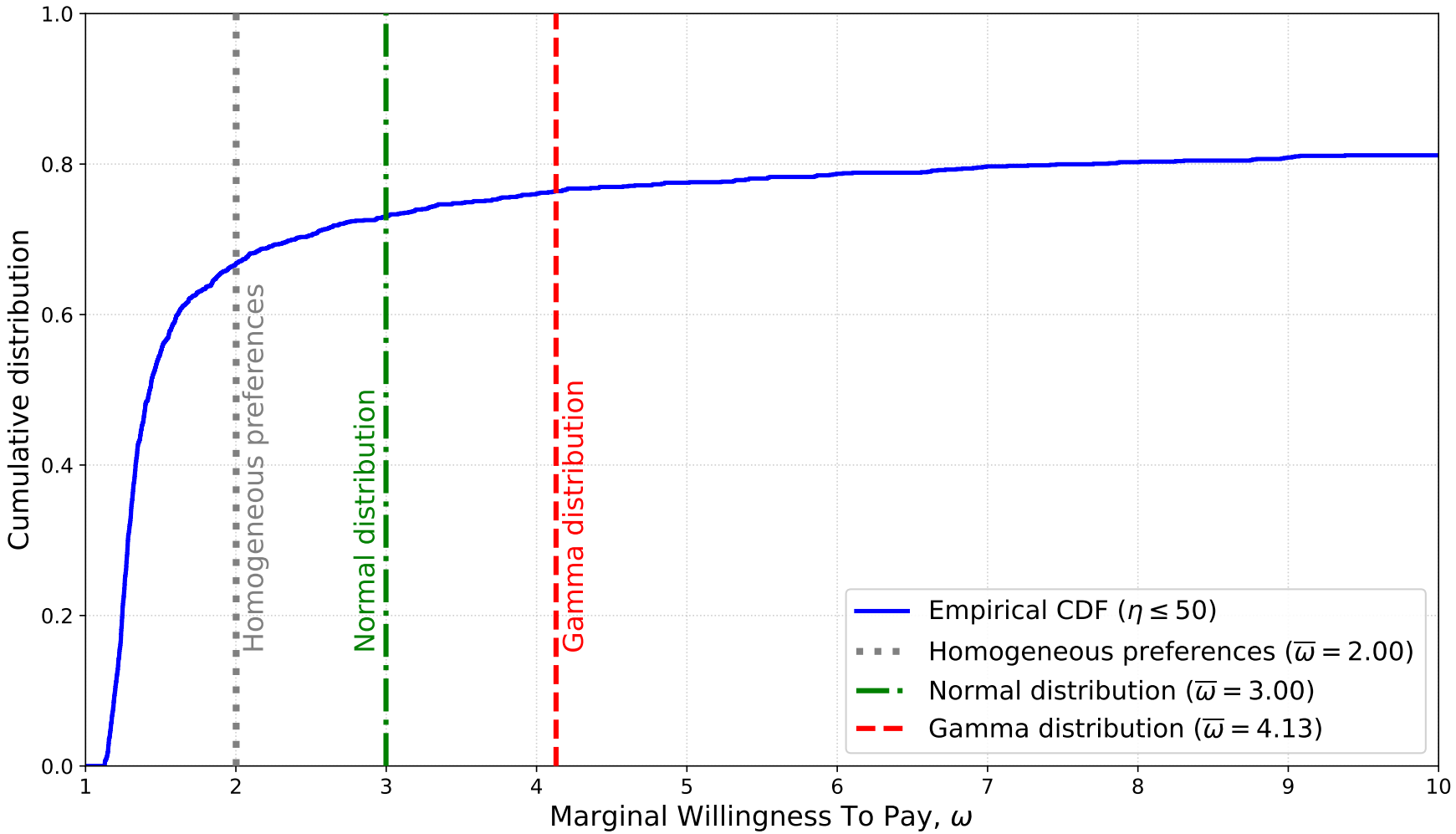

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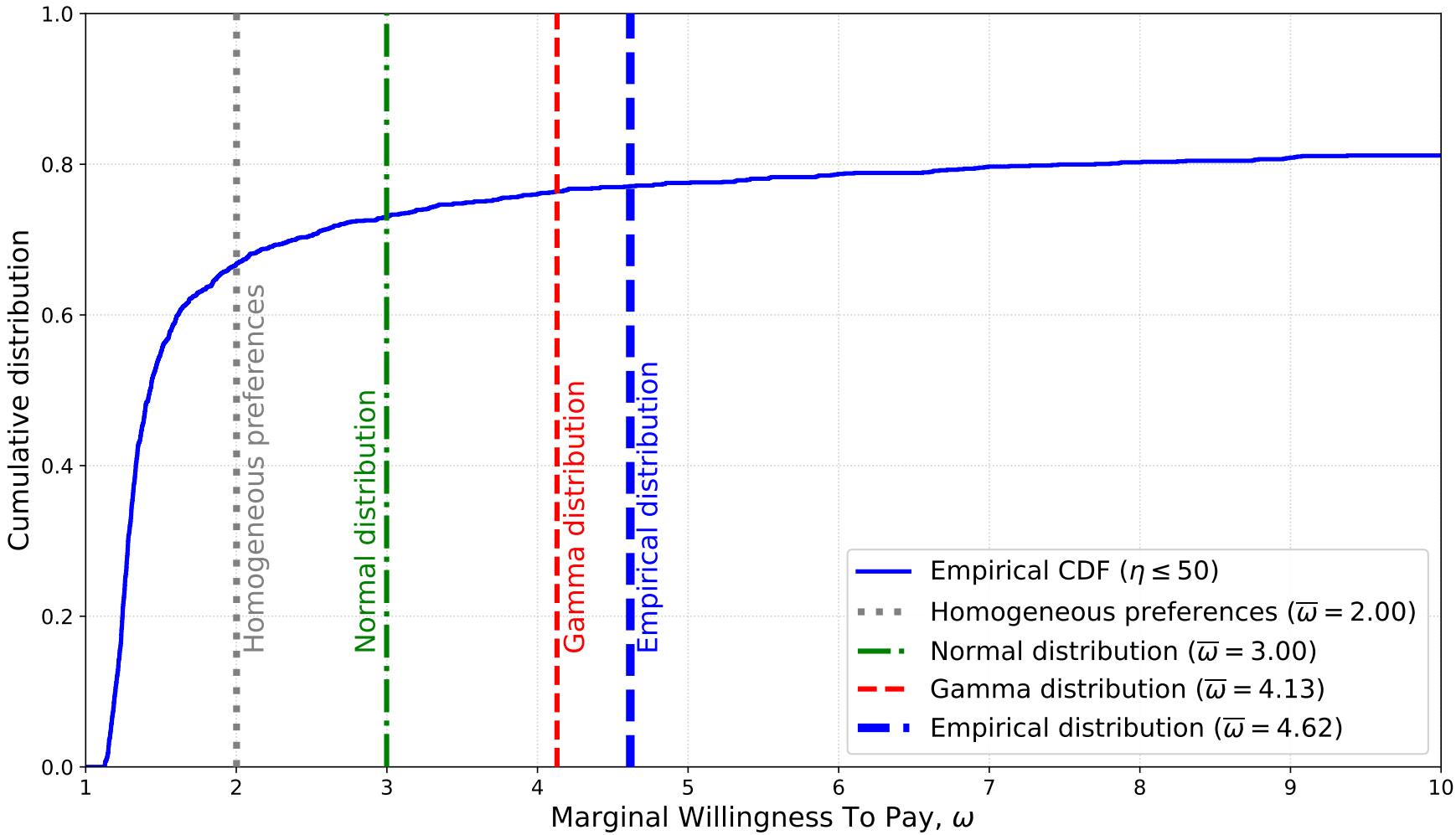
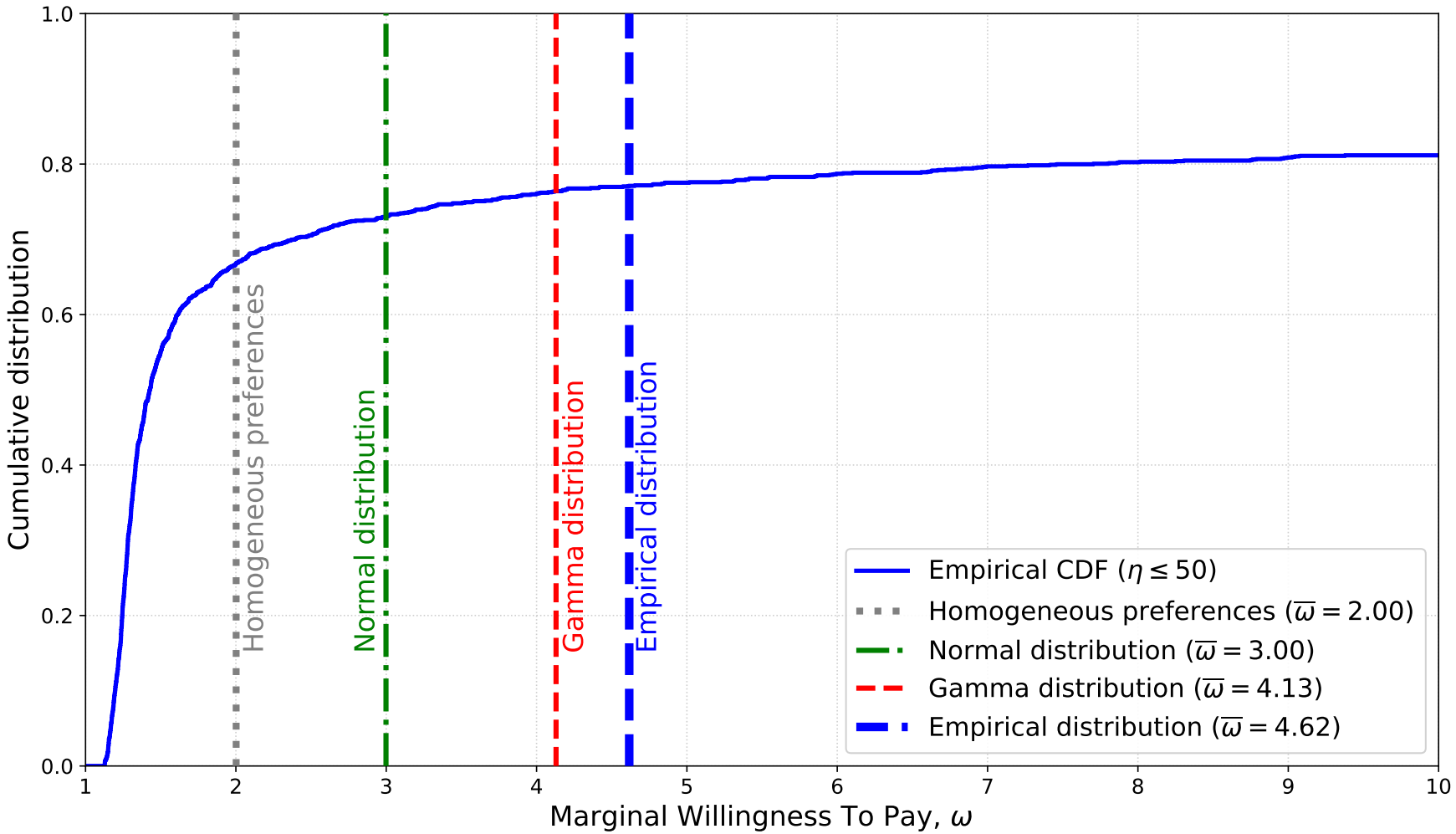


$\Rightarrow$ **Heterogeneity factor** is $h_N = 1.5$ for Normal and $h_\Gamma = 2.06$ for Gamma distribution, and 2.31 for the fully flexible empirical distribution.

7. Illustration of theoretical results



$\Rightarrow$ **Heterogeneity equivalent:** μ_η^* =13.62 (instead of $\mu_\eta \approx 6$) for the Gamma fit, doubling the "representative" complementarity preference estimate.

8. Summary and conclusion

Summary:

- Heterogeneity in complementarity preferences increases the value of environmental goods
- First direct experimental estimates of substitutability preferences reveals that majority lie in complementarity domain, with substantial preference heterogeneity
- If complementarity preferences were normally distributed, mean marginal WTP would increase exponentially in preference heterogeneity
  - Actual η-distribution is heavily skewed and leptokurtic, adding higher-order effects of the heterogeneous preference distribution
    (with nature becoming invaluable w/o truncation or with better fitting Lognormal)

Conclusions:

- Representative agent applications so far miss important preference heterogeneity effect
- Adjustments of the values of environmental public goods due to preference heterogeneity is relevant for CBA & environmental-economic accounting

Bonus

Public Preferences for Index Aggregation

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Malmsten Workshop 2026, Gothenburg

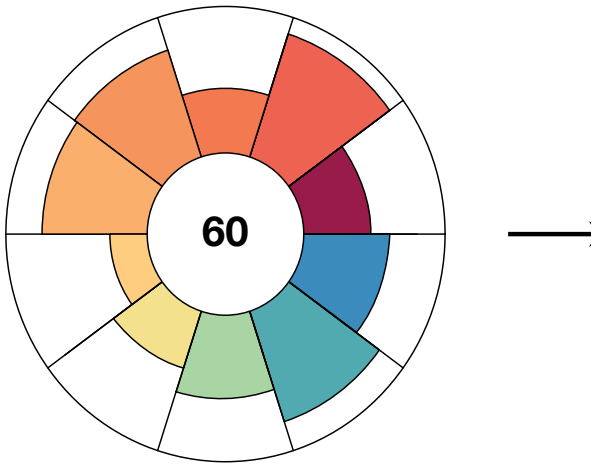
January 22, 2026

ETH zürich

UHH

Public Preferences for Index Aggregation

Current OHI



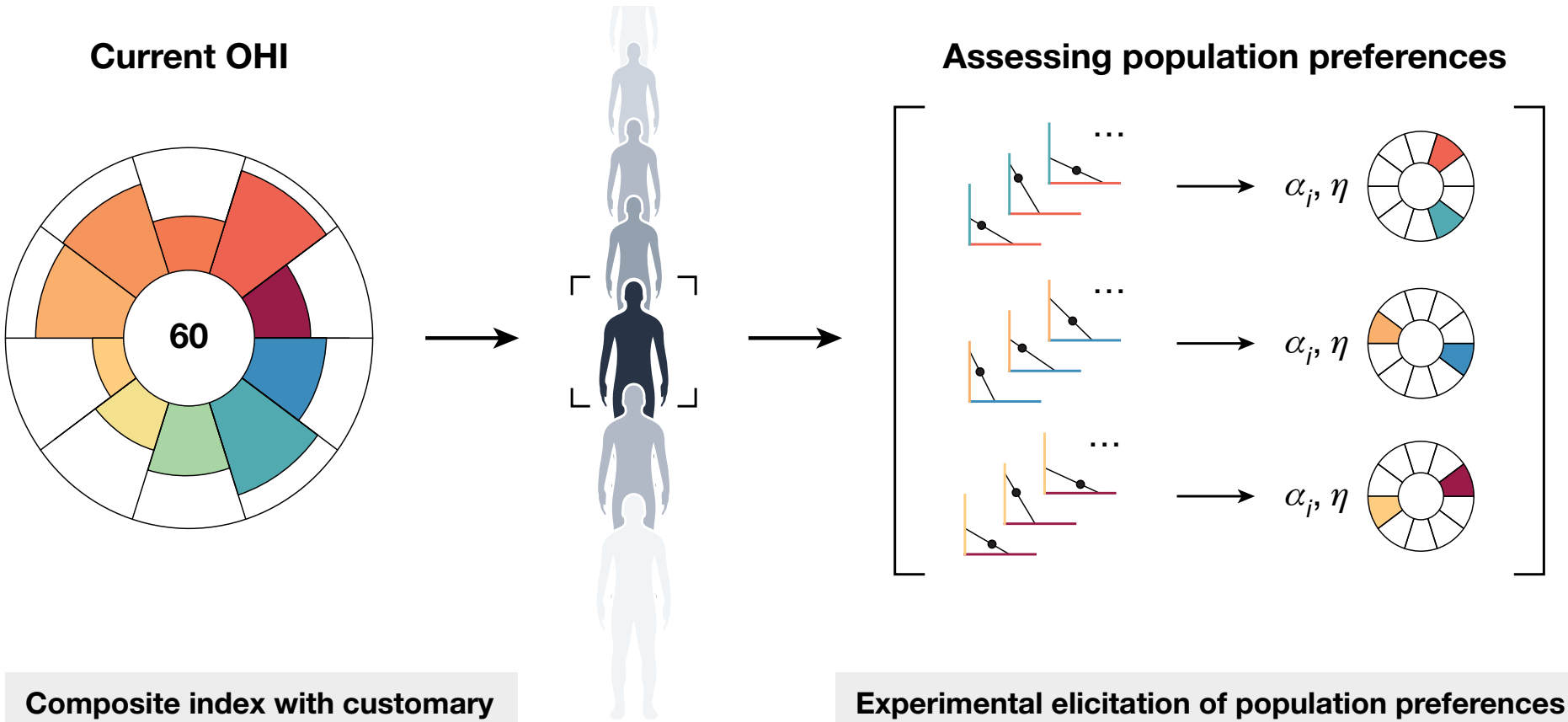
Composite index with customary aggregation assumptions

- Arithmetic mean (AM) for the OHI:

$$AM = \frac{1}{10} \sum_{i=1}^{10} G_i$$

- Equal weights: $\alpha_i = \frac{1}{10}$
- Perfect substitutability: $\eta = 0$

Public Preferences for Index Aggregation



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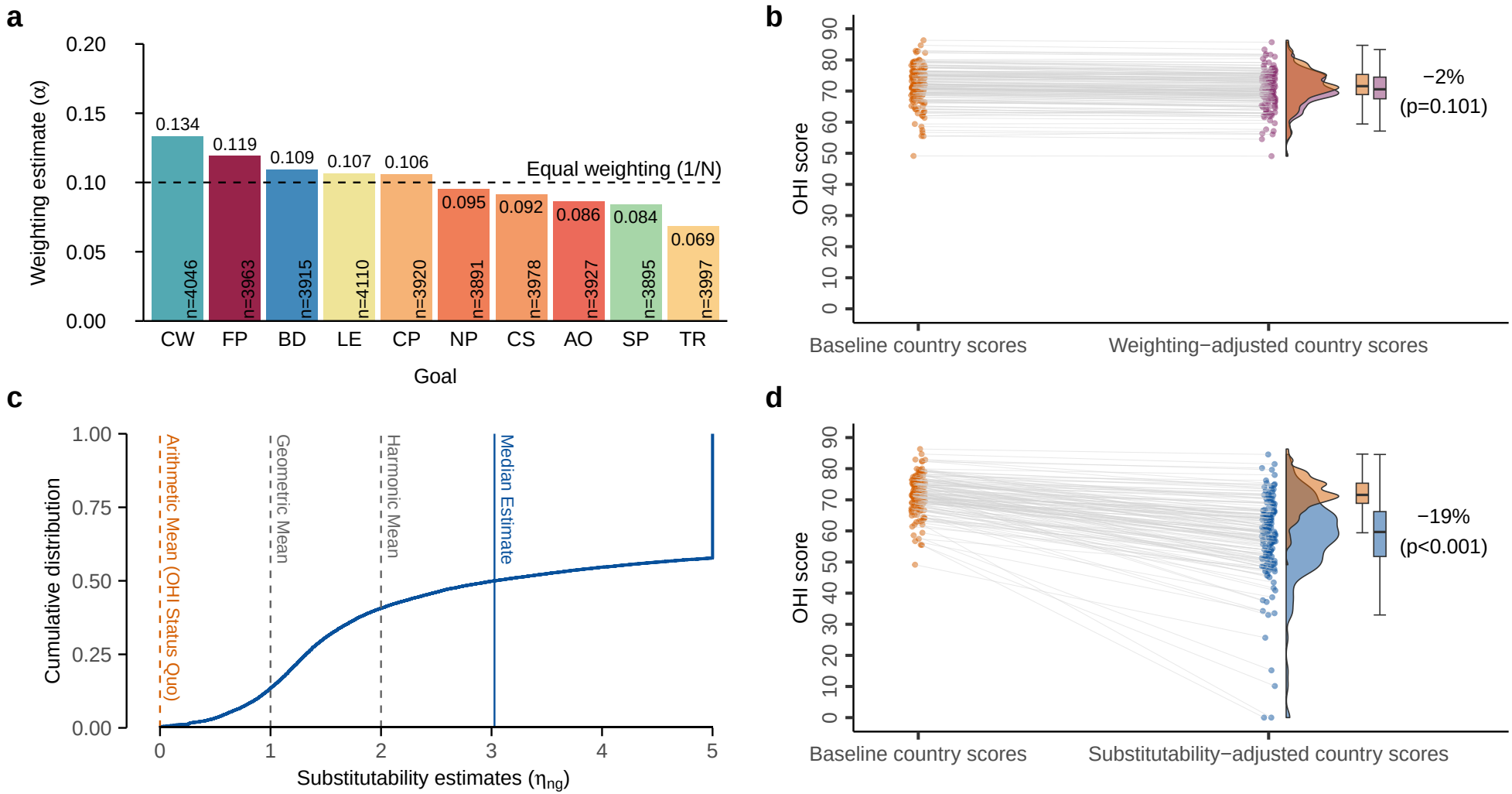
Experimental elicitation of population preferences

- 6,500+ respondents across 12 countries.
- Trade-off experiment with varying budgets to elicit index parameters α (weights) and η (substitutability) for 3 goal pairs per respondent.
- Aggregation across all respondents (per country or globally).

Public Preferences for Index Aggregation

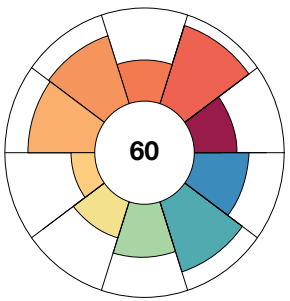


Public Preferences for Index Aggregation

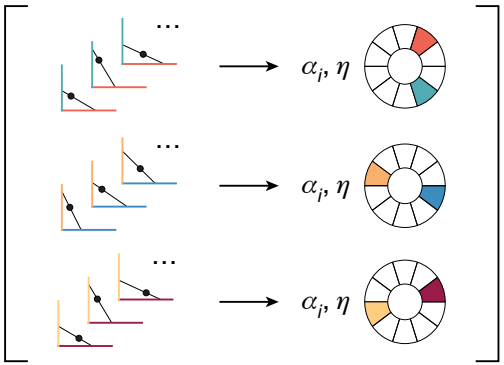
The ten OHI policy goals:

- Natural products
- Artisanal fishing opportunities
- Food provision
- Biodiversity
- Clean waters
- Sense of place
- Coastal protection
- Carbon storage
- Livelihoods and economies
- Tourism and recreation

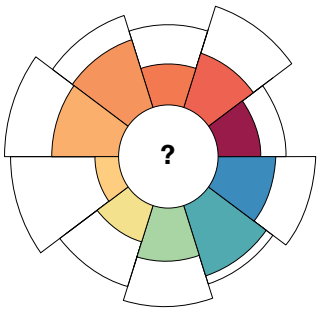
Current OHI



Assessing population preferences



Adjusted OHI



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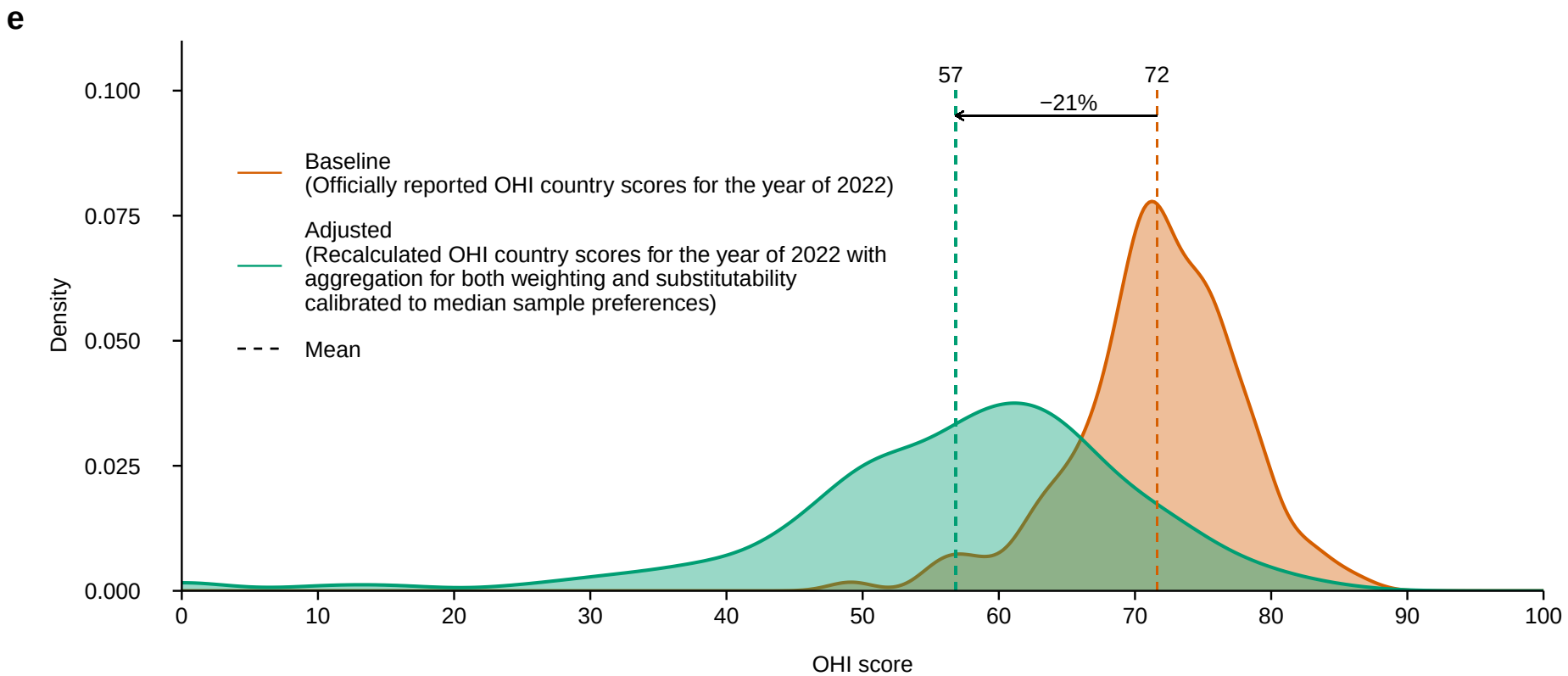
Population preferences challenge customary index assumptions

- Generalized mean (GM) for the OHI:

$$GM = \left(\sum_{i=1}^{10} \alpha_i {G_i}^{1-\eta}\right)^{\frac{1}{1-\eta}}$$

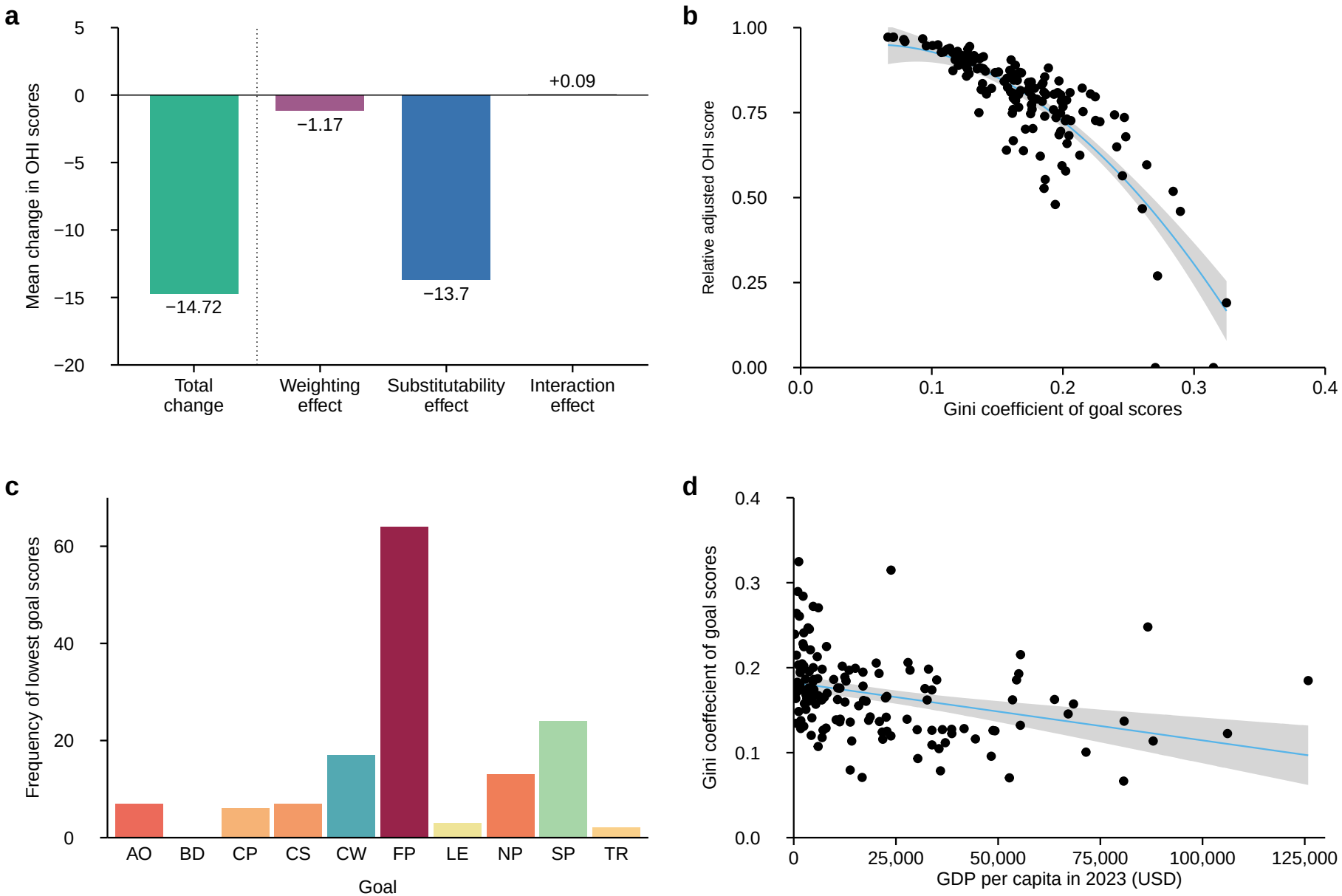
- Unequal weights: $\alpha_i \neq \frac{1}{10}$
- Limited substitutability: $\eta > 0$

Public Preferences for Index Aggregation

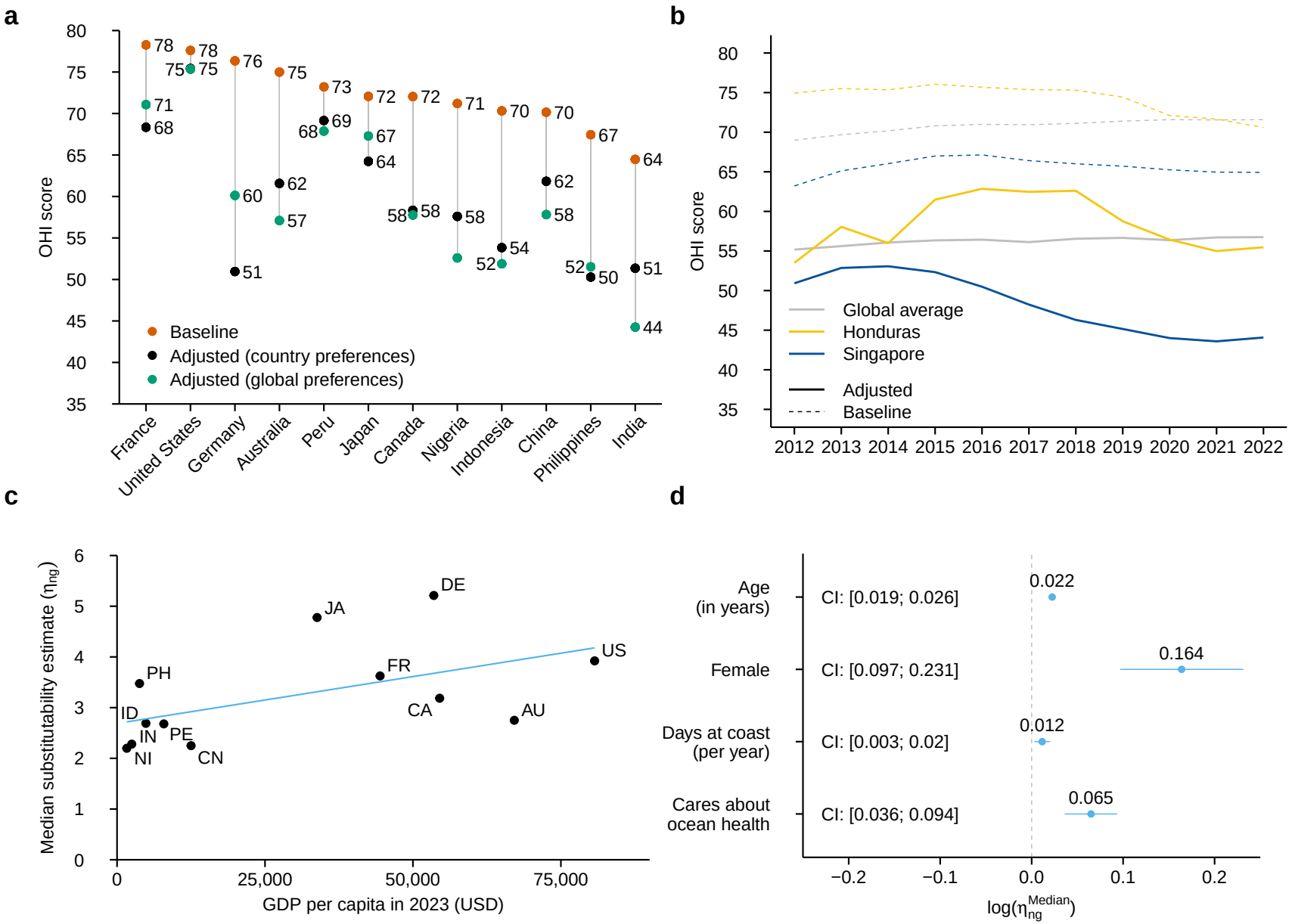


⇒ Moving from the OHI's default arithmetic mean to the generalized mean calibrated with stakeholder preferences reduces the adjusted OHI by >20%

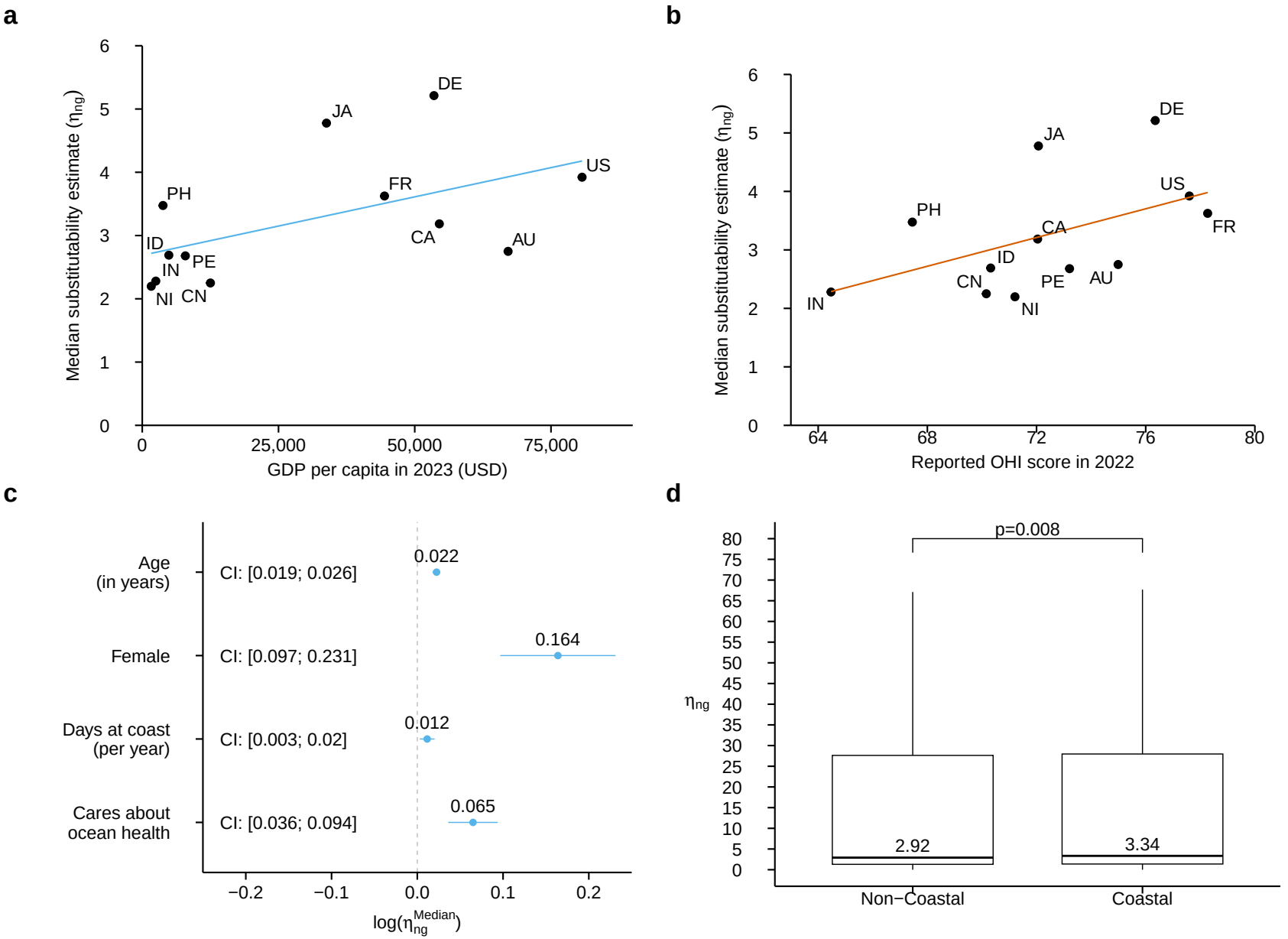
Public Preferences for Index Aggregation



Public Preferences for Index Aggregation

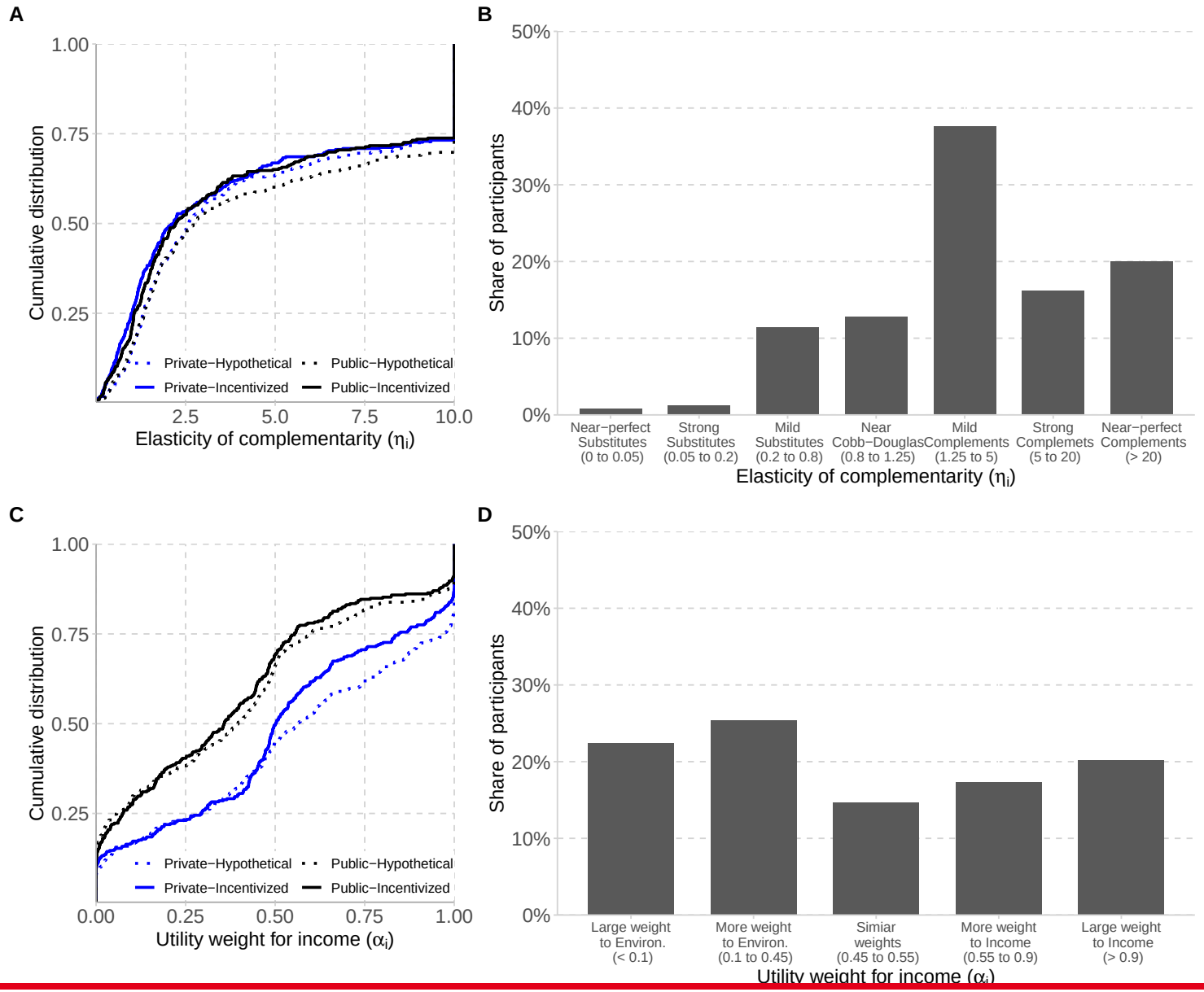


Public Preferences for Index Aggregation

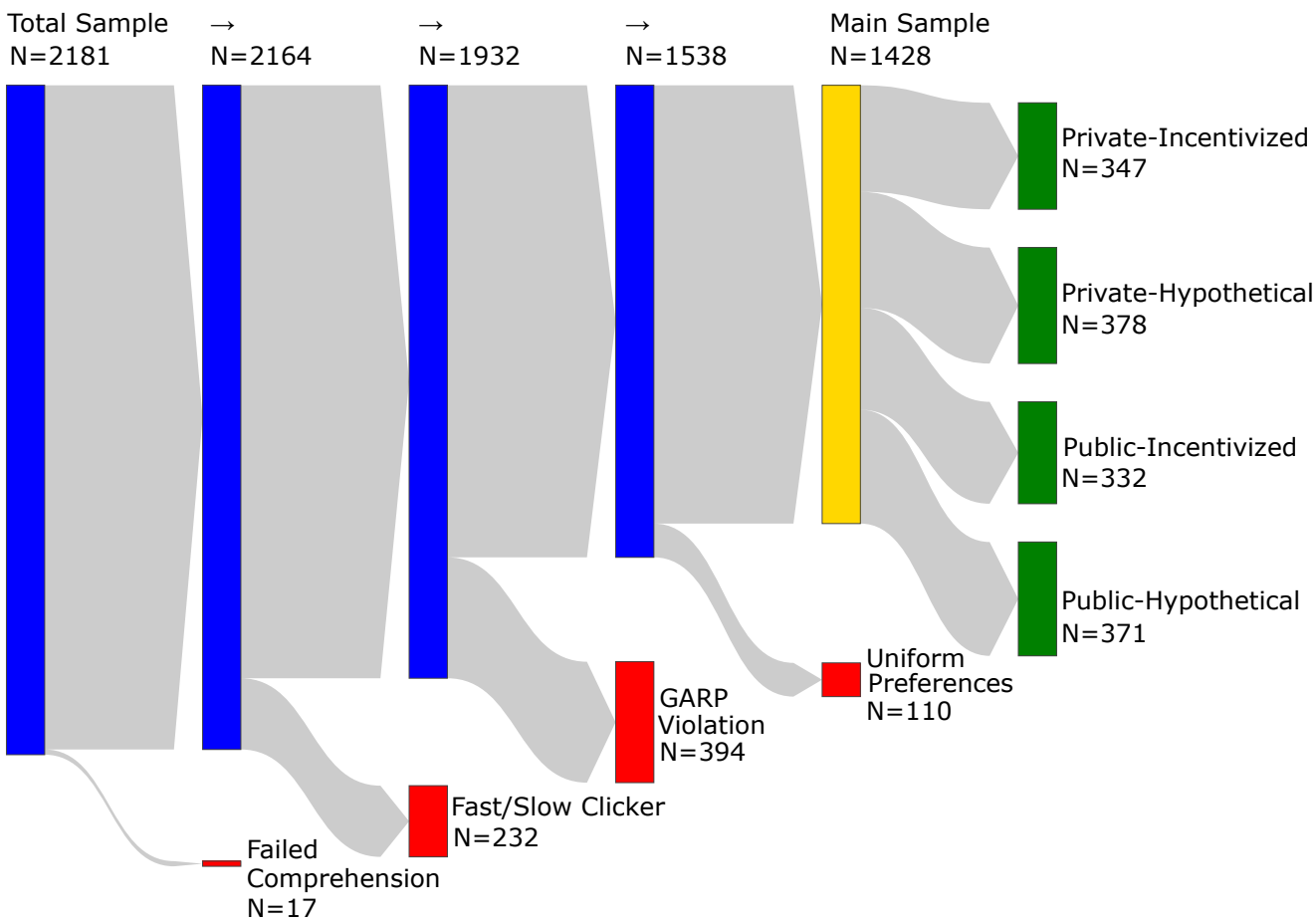


Back-up

Empirical estimates

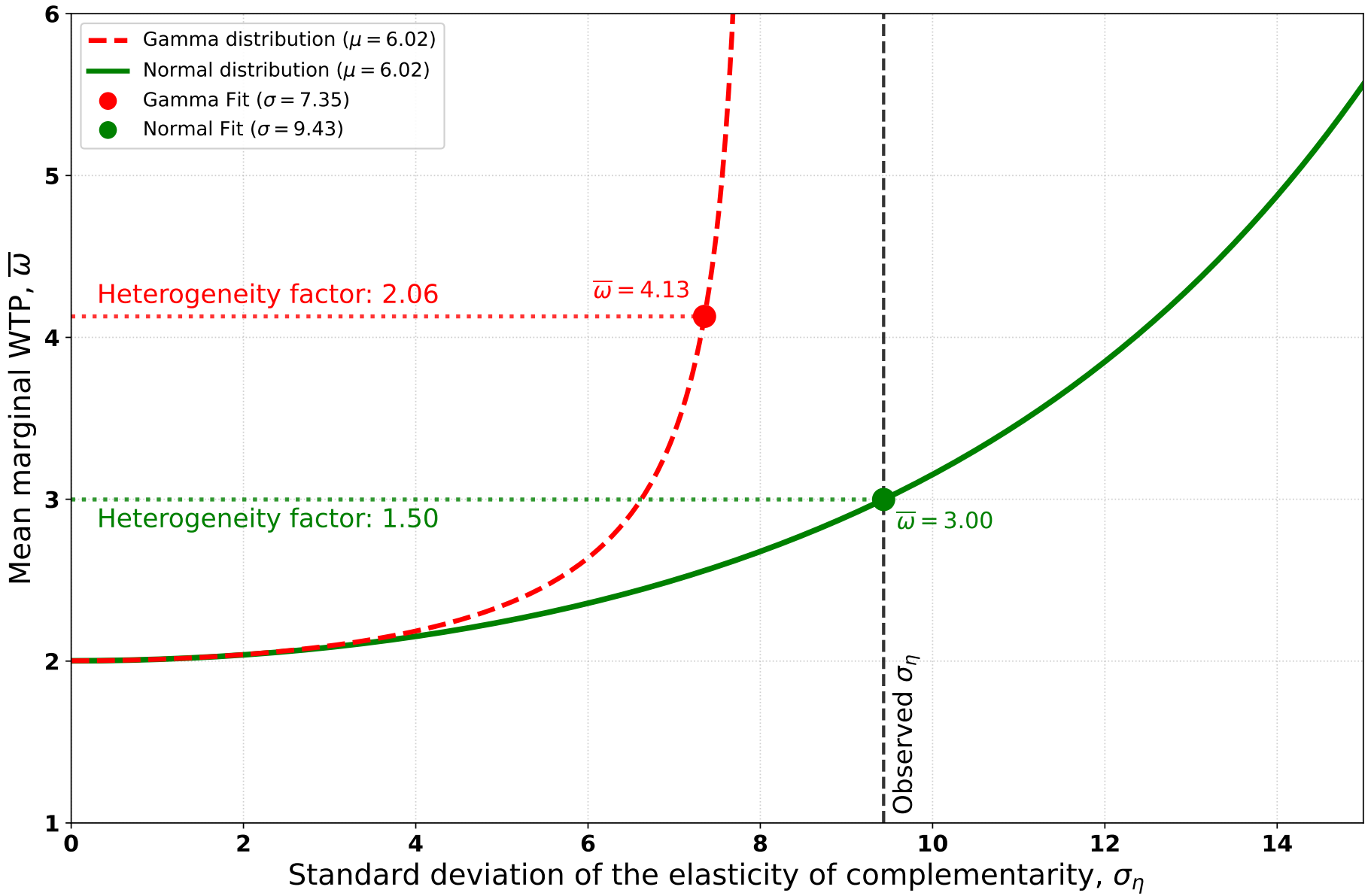


Main sample composition



Notes: Failed Comprehension indicates that a participant failed a comprehension check at least 10 times. *Fast/Slow* clicker includes participants that finsihed the experiment in less than 5 minutes or more than 60 minutes. *Uniform Preferences* denotes participants that are insensitive to relative price changes, meaning that on average they allocated more than 98% of their budget to either income or trees. *GARP Violation* includes all participants below the CCEI threshhold of 0.8.

Heterogeneity equivalent

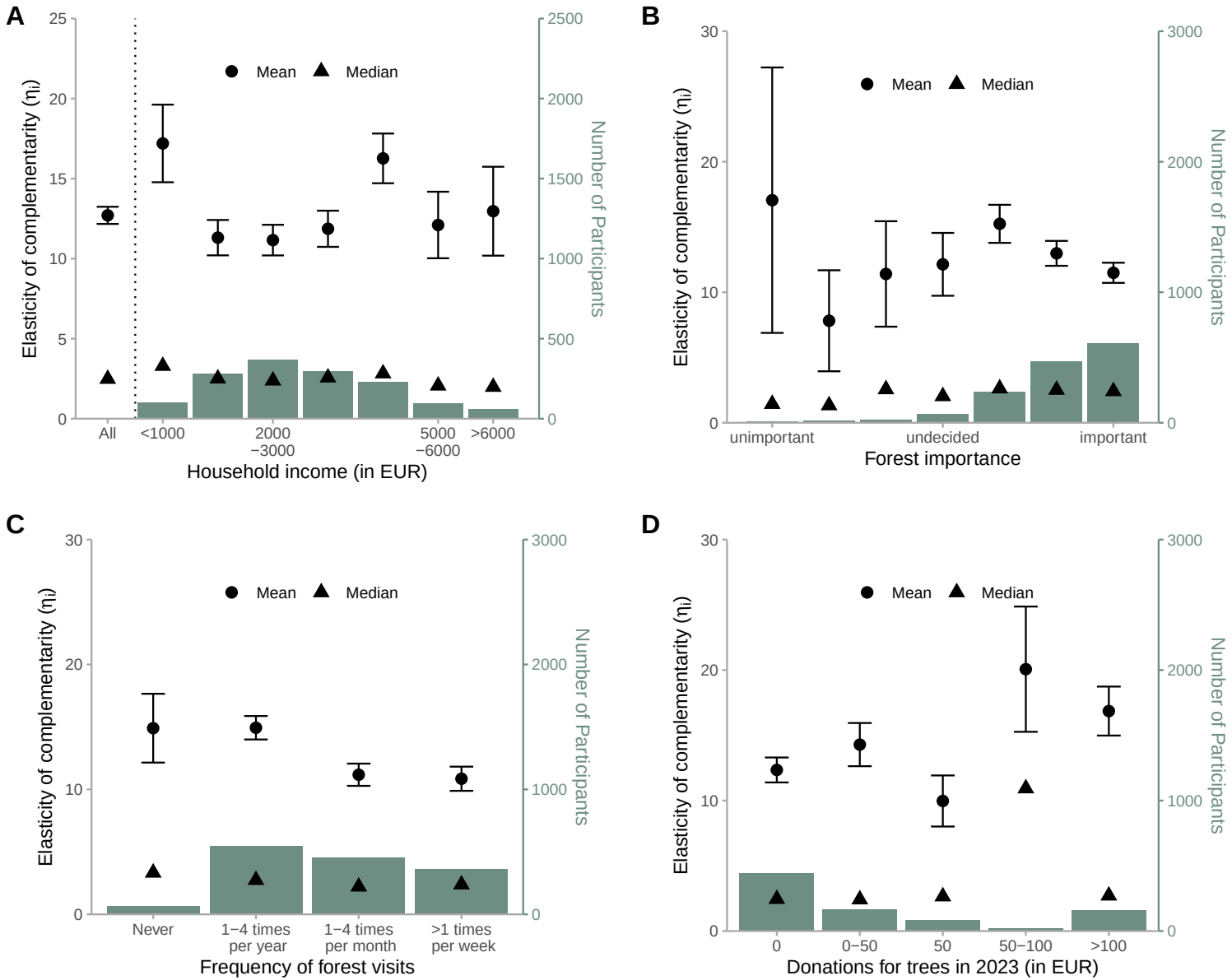


Comparison of Gamma and Normal distributions with cut-offs.

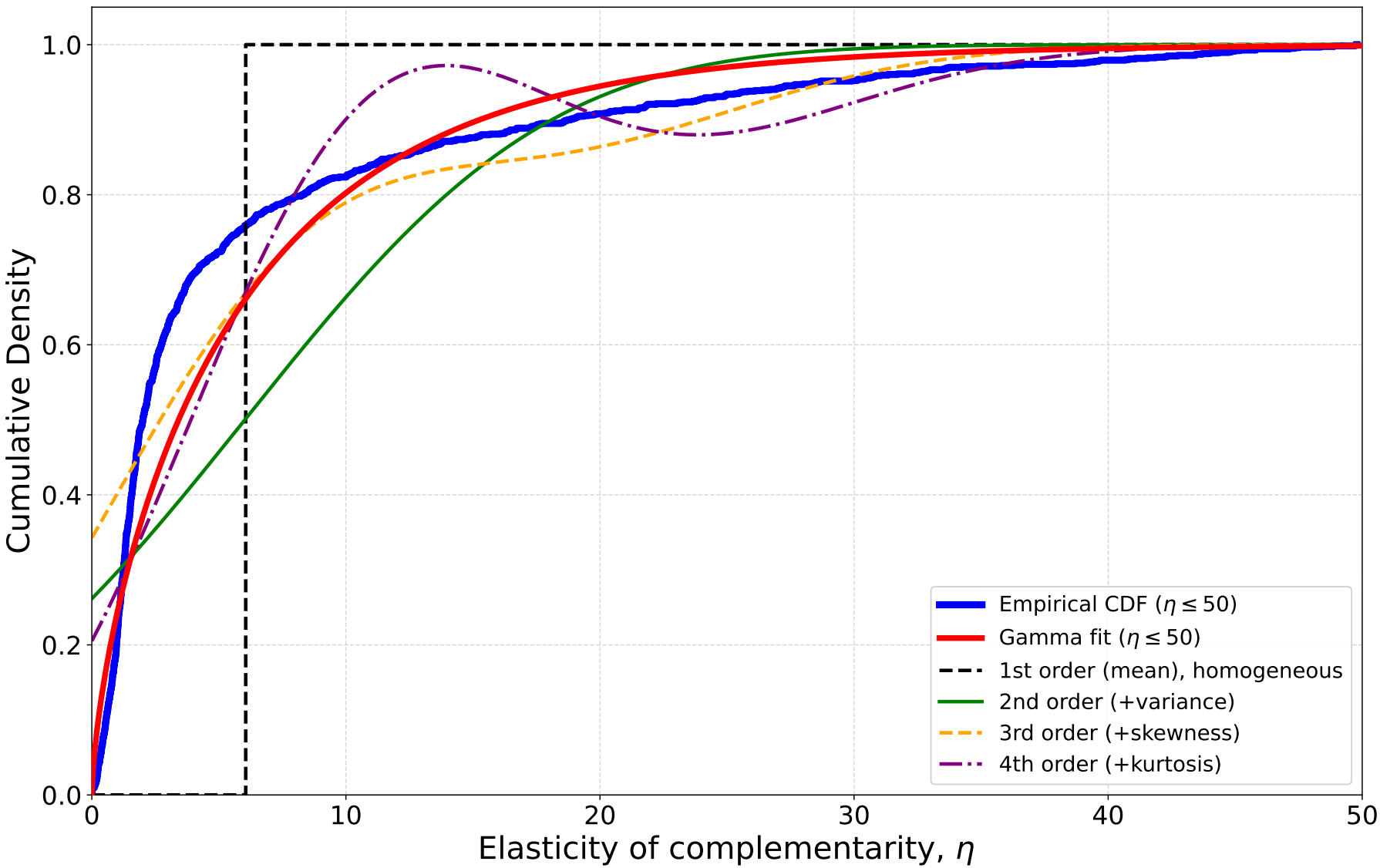
Case	N	Cutoff	Shape (s)	Scale (θ)	$1/\theta$	Mean (μ)	Var (σ^2)
Gamma							
Full Data	1,428	4.1×10^8	0.0753	4,023,314	0.0000	303,034	1.22×10^{12}
95% Pctl.	1,356	258	0.4526	29.0743	0.0344	13.1603	382.6276
90% Pctl.	1,285	62	0.6172	11.4018	0.0877	7.0371	80.2358
$\eta \leq 50$	1,258	50	0.6708	8.9769	0.1114	6.0217	54.0560
$\eta \leq 30$	1,198	30	0.8133	5.3984	0.1852	4.3904	23.7011
$\eta \leq 20$	1,142	20	0.9754	3.4900	0.2865	3.4042	11.8806
$\eta \leq 10$	1,036	10	1.3643	1.6925	0.5908	2.3091	3.9081
Normal							
$\eta \leq 50$	1,258	50	—	—	—	6.0217	89.0243
$\eta \leq 30$	1,198	30	—	—	—	4.3904	35.7428
$\eta \leq 10$	1,036	10	—	—	—	2.3091	4.1836

Notes: The existence of the cumulant generation function for the Normal distribution is always given. For the Gamma distribution, it depends on the truncation level and the goods ratio (Y/E). For $Y/E = 1.1$, the CGF of the Gamma distribution exists up to the truncation level of $\eta \leq 50$. We can more generally formulate critical Y/E levels for the presented truncation levels, which reach from 1.035 for the 95% Pctl. truncation to 1.2035 at $\eta \leq 30$ truncation and 1.805 for $\eta \leq 10$.

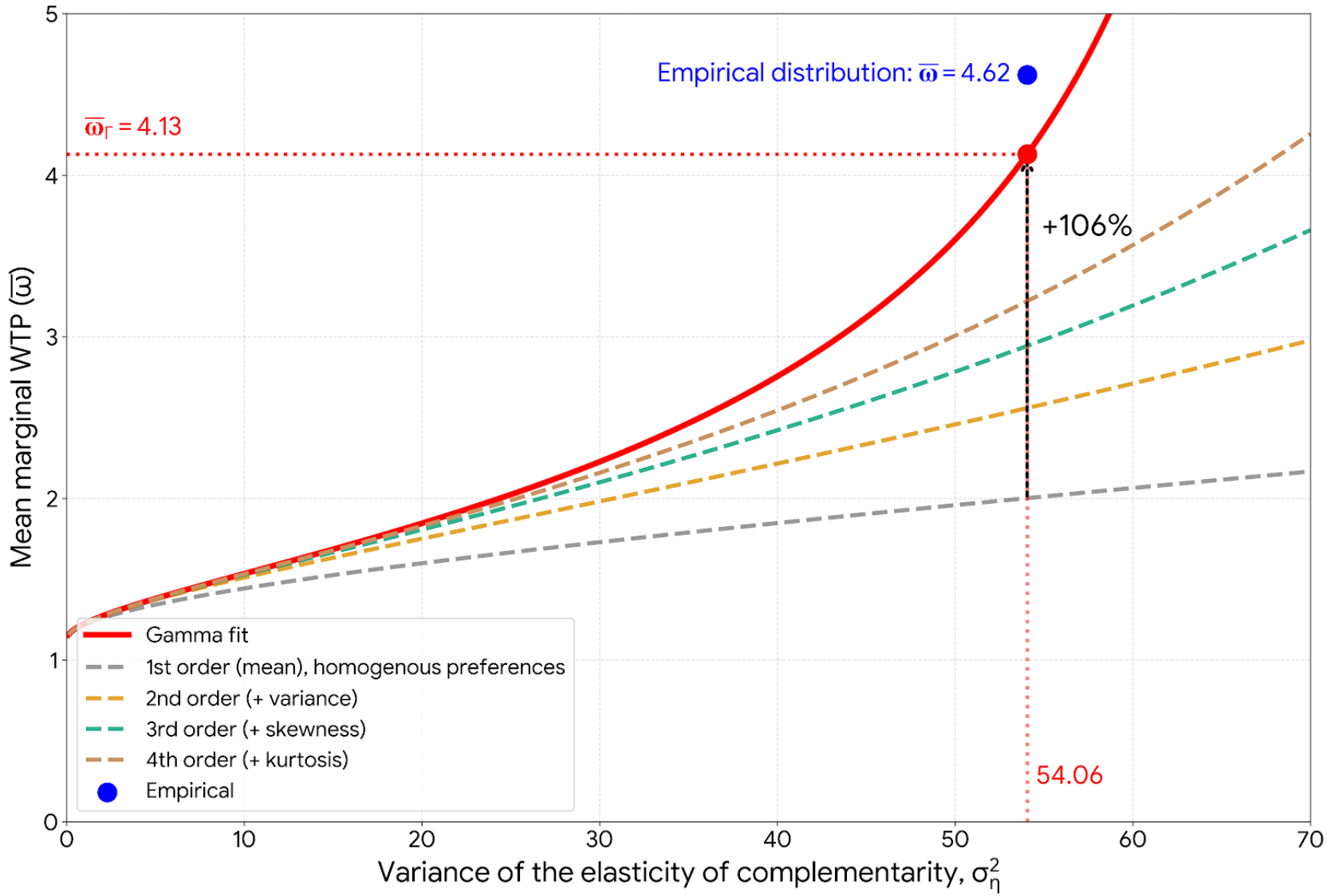
R4: η along income and environmental preferences



Gamma fit CDF approximations



Mean marginal WTP approximations for Gamma fit



Heterogeneously distributed income

The total contribution of heterogeneity to the mean WTP, beyond the homogeneous effect, $g(\mu_\eta, \mu_Y)$ and when considering independence of distributions, is proportional to the sum:

$$\Delta_{\text{Heterogeneity}} \propto \sigma_\eta^2 \left(\ln\left(\frac{\mu_Y}{E}\right)\right)^2 + \sigma_Y^2 \frac{\mu_\eta(\mu_\eta - 1)}{\mu_Y^2}.$$

(1) **Dominantly negative higher-order moments**
$\Rightarrow$ Not possible in fitted Gamma case

(2) **Negative covariance**
Heterogeneity contribution includes a covariance term, which can overcompensate preference heterogeneity if it is larger than a critical value:

$$\sigma_{\eta Y}^{\text{crit}(\eta)} = -\frac{\mu_Y (\ln\left(\frac{\mu_Y}{E}\right))^2}{2 \cdot \left(1 + \mu_\eta \ln\left(\frac{\mu_Y}{E}\right)\right)} \sigma_\eta^2 \tag{17}$$

With our Gamma fit ($\mu_\eta = 6.02$, $\sigma_\eta^2 = 54.05$, $Y/E = 1.1$), the critical covariance is approximately $\sigma_{\eta Y}^{\text{crit}(\eta)} = -0.17 \Rightarrow$ individuals with higher complementarity preference would predominantly need to be the lowest income earners.

Tabelle 1: Summary Statistics of Outlier Sensitivity Analysis.

	Median	Mean	SD	Min	Max
η_{Main}	2.48	12.70	20.27	0.00	63.63
$\eta_{Ex-Outlier}$	2.97	20.78	35.38	0.00	111.44
α_{Main}	0.47	0.47	0.35	0.00	1.00
$\alpha_{Ex-Outlier}$	0.46	0.47	0.37	0.00	1.00
Observations	1,428				

Notes: This table shows summary statistics of the estimated preference parameters for the main sample using (1) our main specification (2) excluding potential outlier decisions. In both cases the estimates for η are winsorized at the upper 90th percentile.