# Peer prediction markets to elicit unverifiable information

Aurélien Baillon [1]    Cem Peker [2]    Sophie van der Zee [3]

January 17, 2023

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# Background

Education:

- PhD in Economics (30.03.2023, Tinbergen Institute, Netherlands)
- BSc in Industrial Engineering, Bogazici University

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**Publications:**

- Peker, C. (2022). Extracting the collective wisdom in probabilistic judgments. *Theory and Decision*. doi: 10.1007/s11238-022-09899-4
  → Decision Analysis Society 2022 Student Paper Award nominee
- Peker, C. (2022). Incentives for self-extremized expert judgments to alleviate the shared-information problem. *Decision*. doi.org: 10.1037/dec0000198

# Background

Ongoing work:

- Peer prediction markets to elicit unverifiable information
  (joint with Aurélien Baillon and Sophie van der Zee)

- Robust recalibration of aggregate probability forecasts using meta-beliefs
  (joint with Tom Wilkening)

- Bayesian voters may distort an accurate majority in interconnected decision problems

- Using prediction interval skewness to improve forecast accuracy
  (joint with Yael Grushka-Cockayne, Victor R.R. Jose, Jacob Rittich and Jack Soll)

- A scoring rule for incentivizing self-knowledge in survey responses

More info: https://cempeker.github.io/

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Response is informative if you....

1. ...recall your experience accurately (cognitive effort)
2. ...report honestly (incentives to lie?)

# Imagine a Covid-19 survey...

"Have you stood less than 6 feet apart from another person in a queue yesterday?"

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Incentivize carefully considered and truthful answers?

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Incentivize carefully considered and truthful answers?

**Your answer is unverifiable!**

"Have you stood less than 6 feet apart from another person in a queue yesterday?"

**Incentivize truthfulness when the truth is unverifiable?**

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**Incentivize truthfulness when the truth is unverifiable?**

**Peer Prediction** (Miller et al., 2005):

- Your honest answer $\leftrightarrow$ Your prediction on others' answers

# Carefully considered and truthful answers

"Have you stood less than 6 feet apart from another person in a queue yesterday?"

**Incentivize truthfulness when the truth is unverifiable?**

**Peer Prediction** (Miller et al., 2005):

- Your honest answer ↔ Your prediction on others' answers
- **Your prediction on others' answers is verifiable!**
  → Truthful answer can be inferred.

Your prediction on others' answers is verifiable!

This paper: **Peer-Prediction Market (PPM)**

- One-shot market, buy/sell a single asset

- Trade $\equiv$ A bet on others' answers

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- Trade $\equiv$ A bet on others' answers

- Trades reveal carefully considered and truthful answers

- Theory & evidence from 2 experimental studies

# The Formal Framework

## The framework

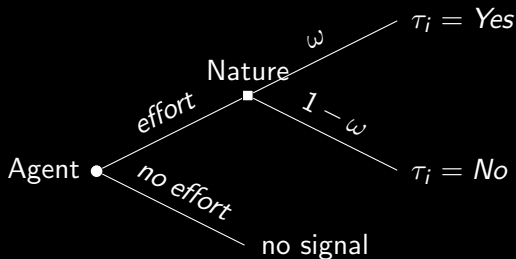- *Center* asks a binary question $\{Yes, No\}$
- $N$ risk-neutral *agents*

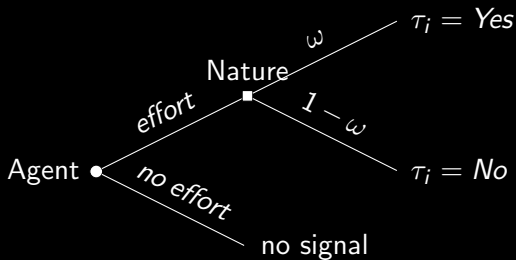- *Center* asks a binary question $\{Yes, No\}$
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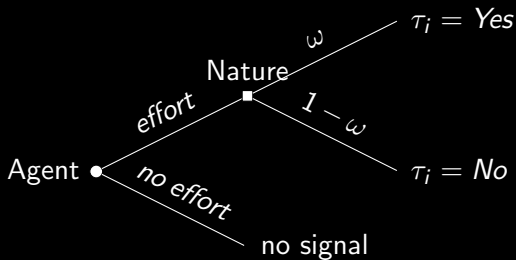- Signal $\tau_i \equiv$ Agent $i$'s honest answer

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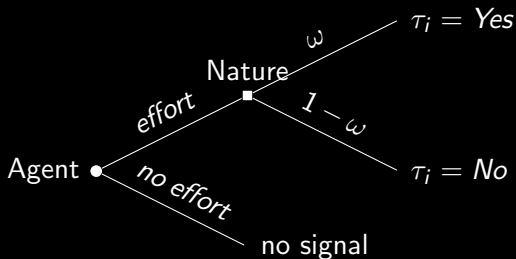Signal $\tau_i \equiv$ honest answer. Why is $\tau_i$ costly?

"Have you stood less than 6 feet apart from another person in a queue yesterday?"

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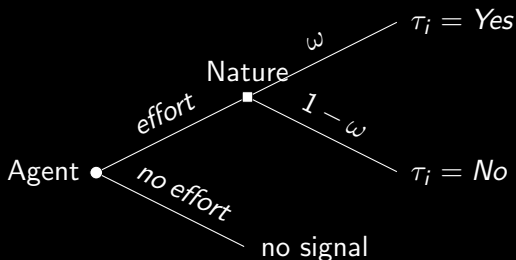
**Mental effort to remember, Unwilling to recall**

Assumptions:

- Common prior expectation $E[\omega]$ on $\omega$.
- $E[\omega]$ is public knowledge.
- Agents follow Bayesian updating.

# The framework
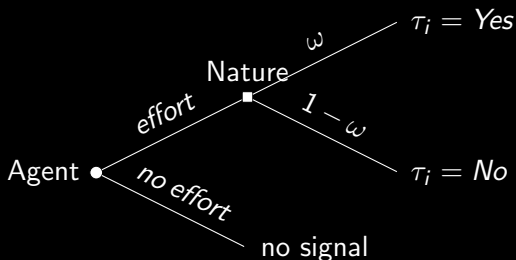


3 groups of agents with posterior expectations:

$$E[\omega|\text{effort and } \tau_i = Yes]$$
$$E[\omega|\text{effort and } \tau_i = No]$$
$$E[\omega|\text{no effort}] = \text{Prior} = E[\omega]$$

Nature

$\omega$   $\tau_i = Yes$

effort

$1 - \omega$

Agent

no effort

$\tau_i = No$

no signal

Posterior expectations satisfy:

$E[\omega|\tau_i = Yes] > E[\omega] > E[\omega|\tau_i = No]$

"Yes"-types expect $\omega > E[\omega] = $ prior.

"No"-types expect $\omega < E[\omega] = $ prior.
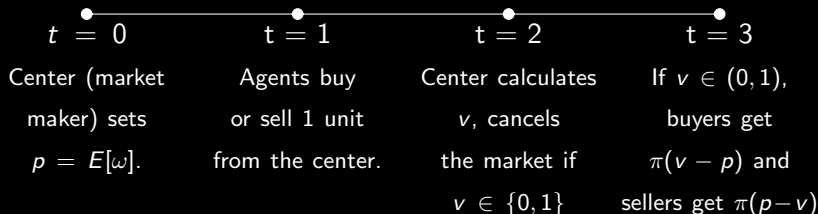
Peer prediction market

## The mechanism

One-shot market

- Single asset
- Asset price $= p = E[\omega]$
- Asset value $= v =$ proportion of agents who buy

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One-shot market

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| $t = 0$ | $t = 1$ | $t = 2$ | $t = 3$ |
|---|---|---|---|
| Center (market maker) sets $p = E[\omega]$. | Agents buy or sell 1 unit from the center. | Center calculates $v$, cancels the market if $v \in \{0, 1\}$ | If $v \in (0, 1)$, buyers get $\pi(v - p)$ and sellers get $\pi(p - v)$ |

## The mechanism

Numerical example:

- Currency is dollar, $\pi = 10$

- Price: $p = E[\omega] = 0.5$

- 40% of the participants buy, $v = 0.4$

- Buyer's payoff: $10\,(0.4 - 0.5) = -\$1$

- Seller's payoff: $10\,(0.5 - 0.4) = \$1$

Strategy = Effort or not + probability of buy in various situations

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Agent $i$'s full strategy profile $= (e_i, R_i, R_i^{no}, R_i^{yes})$

- $e_i \in \{0, 1\}$ effort or no effort
- $R_i$ probability of buy if $e_i = 0$,
- $R_i^{no}$ probability of buy if $e_i = 1$ and $\tau_i = No$,
- $R_i^{yes}$ probability of buy if $e_i = 1$ and $\tau_i = Yes$.

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Center would like: $e_i = 1$, $R_i^{no} = 0$, and $R_i^{yes} = 1$.

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Center would like: $e_i = 1$, $R_i^{no} = 0$, and $R_i^{yes} = 1$.
$\implies$ **Truthful strategy**: Trades reflect honest answers.

**Assumption**. The following are **common knowledge**:

- The market mechanism
- Signal technology, beliefs, costs and the strategy space.
- Risk-neutrality and Bayesianism of agents.

Ensures that we have a *Bayesian game* (Osborne and Rubinstein, 1994, Definition 25.1).

For convenience, we let $N \to \infty$.

# Equilibrium analysis

**Truthful equilibrium**: For $N \to \infty$, truthful strategy is a Nash equilibrium if the rewards are scaled sufficiently high such that

$$\frac{c_i}{\pi} < E[\omega]\left(E[\omega|\tau_i = \textit{Yes}] - E[\omega]\right) + (1 - E[\omega])\left(E[\omega] - E[\omega|\tau_i = \textit{No}]\right)$$

for all $i \in \{1, \dots, N\}$

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$$\frac{c_i}{\pi} < E[\omega]\left(E[\omega|\tau_i = Yes] - E[\omega]\right) + \left(1 - E[\omega]\right)\left(E[\omega] - E[\omega|\tau_i = No]\right)$$

for all $i \in \{1, \dots, N\}$

In the truthful equilibrium...

- All agents exert effort
- Yes-types buy, No-types sell
- Truthful answer $\equiv$ Equilibrium trade

**Truthful equilibrium**: Full effort, Yes-types buy, No-types sell

How?

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How? Suppose,

- Agent $i$ exerts effort ($e_i = 1$)
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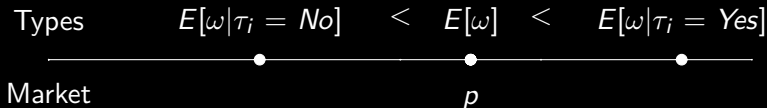- All agents $j \neq i$ are truthful

Types      $E[\omega | \tau_i = No]$    $<$    $E[\omega]$    $<$    $E[\omega | \tau_i = Yes]$

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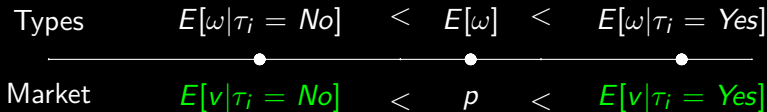- All agents $j \neq i$ are truthful

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Market $\qquad\qquad\qquad\qquad\qquad\qquad\qquad p$

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| Types | $E[\omega \mid \tau_i = No]$ | $<$ | $E[\omega]$ | $<$ | $E[\omega \mid \tau_i = Yes]$ |
|---|---|---|---|---|---|

| Market | $E[v \mid \tau_i = No]$ | $<$ | $p$ | $<$ | $E[v \mid \tau_i = Yes]$ |
|---|---|---|---|---|---|

Asset value ($v$) $\equiv$ Proportion of buyers $\rightarrow$ Proportion of Yes-type ($\omega$)

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Optimal: Buy if $\tau_i = Yes$, sell if $\tau_i = No$

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|---|---|---|---|---|---|

Optimal: Buy if $\tau_i = Yes$, sell if $\tau_i = No$
Profitable trades $\to$ Incentive to "learn" your type $\to e_i = 1$

**Multiple equilibria**

**No-effort equilibrium**: If $c_i > \pi$ for all $i \in \{1, \dots, N\}$, then Nash equilibria are characterized by $e_i = 0$ and $R_i \in \{0, E[\omega], 1\}$.
Expected payoffs are 0.

$\rightarrow$ No effort when costs are too high.

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$\rightarrow$ No effort when costs are too high.

**Partial effort equilibrium**: There are NE in which $K < N$ agents exert no effort and buy with probability $E[\omega]$ while the other agents are truthful.

$\rightarrow$ People with low cost exert effort, others do not.

**Multiple equilibria**

**All-buy or all-sell**: There exists Nash equilibria such that $e_i = 0$ and $R_i = 0$ or $R_i = 1$ for all $i$. Expected payoffs are 0.

**Multiple equilibria**

**All-buy or all-sell**: There exists Nash equilibria such that $e_i = 0$ and $R_i = 0$ or $R_i = 1$ for all $i$. Expected payoffs are 0.

**Truthful equilibrium: Strictly higher payoff than no-effort, all-buy and all-sell equilibria**

"Have you stood less than 6 feet apart from another person in a queue yesterday?"

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Reporting "Yes" is shameful $\rightarrow$ higher cost?

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- **Asymmetric reporting cost**: Cost $a_i \geq 0$ of reporting "Yes", no matter (presence of) signal.

- **Deception cost**: The cost $d_i \geq 0$ of reporting "Yes" when $\tau_i = No$ or "No" when $\tau_i = Yes$.

"Have you stood less than 6 feet apart from another person in a queue yesterday?"

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**Truthful equilibrium if $\pi$ is scaled appropriately**

# Experimental Evidence

Two experimental studies.

Study 1:

- Closely follows the theoretical model.
- Real effort task.

Study 2:

- Survey on behavior under Covid-19 safety guidelines.
- Psychological costs & practical feasibility.

One of the boxes is selected at random (Q="more yellow" or I="less yellow").

Guess which one.

Box Q

Box I

100 balls
More than **60** 🟡

100 balls
More than **40** 🔵

Total : 120 🟡 , 80 🔵

One of the boxes is selected at random (Q="more yellow" or I="less yellow").

Guess which one. Want to see a ball from the selected box?

| 0 | 0 | 1 | 1 | 0 | 1 |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 1 | 0 | 0 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 0 | 1 |

Count the number of 0s and you draw..

  OR  

Color of your draw $\equiv$ signal

- Let's say a yellow draw is equivalent to ($\tau_i = Yes$).
- $E[\omega] = 0.6$ (common prior expectation on prop. yellow).

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- $E[\omega] = 0.6$ (common prior expectation on prop. yellow).
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- Yes-types (yellow draw) should pick Box Q ($\equiv$ Buying)

- Flat fee: £3.25 completion fee.

- Accuracy incentives: £3.25 $\pm$ 0.20 per prediction task if the pick is correct or not.

- PPM: £3.25 + PPM incentives.
  Bonus in each question:
  (% of people who pick the same box) $-$ (prior).

"Accuracy" is a benchmark for verifiable tasks.

- Online experiment, May 2020

- 210 U.S. citizens, students, recruited on Prolific

- 10 tasks (10 pairs of boxes, 10 matrices).

Proportion of subjects who complete the effort task
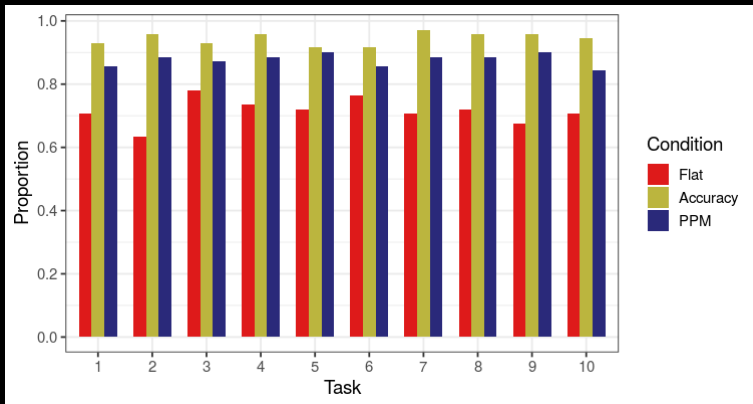


*Accuracy* > *PPM* > *Flat* in effort elicitation
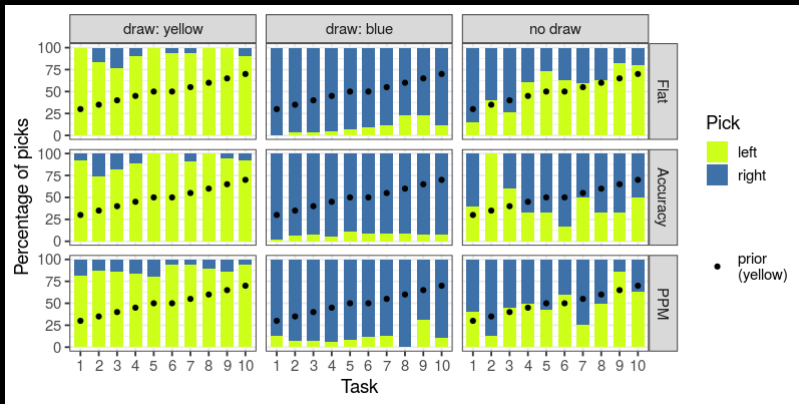
Picks are as predicted by the truthful equilibrium.

# Marginal effects, logistic regression

| Dep. var.: P(effort task completed) | | | | |
|---|---|---|---|---|
| | (whole sample) | | (filtered sample) | |
| | (1) | (2) | (3) | (4) |
| PPM | 0.10** | 0.09** | 0.10** | 0.08** |
| | (0.03) | (0.03) | (0.03) | (0.03) |
| Accuracy | 0.18*** | 0.18*** | 0.18*** | 0.18*** |
| | (0.03) | (0.03) | (0.03) | (0.03) |
| Age | | −0.00 | | −0.00 |
| | | (0.00) | | (0.00) |
| Female? | | 0.04 | | 0.04 |
| | | (0.03) | | (0.03) |
| US resident? | | −0.02 | | −0.02 |
| | | (0.06) | | (0.06) |
| Num. obs. | 2100 | 2070 | 2060 | 2030 |

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{+}p < 0.1$

PPM can elicit effort when incentives for accuracy are not feasible (unverifiable questions).

Study 1: Simple task, carefully controlled setup.

Study 2: Online field experiment

- Health & safety guidelines during the Covid-19 pandemic.
- Did people follow them? **(Difficult to measure)**

Study 1: Simple task, carefully controlled setup.

Study 2: Online field experiment

- Health & safety guidelines during the Covid-19 pandemic.
- Did people follow them? **(Difficult to measure)**

- Would they self-report their unsafe behavior? **(Unverifiable)**
- Covid-19 survey with PPM incentives.
- Weekly survey in the UK, 3 weeks.

**Question 2 of 8 (show instructions)**

Please try to remember how many times you were in the following situation:

**I was seated less than 2 metres away from someone who is not part of my household in a restaurant/cafe/bar at least once in the last 7 days.**

| **True** (picked by 44% last week) | **False** (picked by 56% last week) |
|---|---|

Submit

**Question 2 of 8 (**show instructions**)**

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"True" could be underreported.

We test if PPM elicits a higher % of "True" responses

## Study 2 - True/False statements

| | |
|---|---|
| 1. | I have been in an elevator with another person in it at least once in the last 7 days |
| 2. | I may have stood less than 2 metres away from the person in front in a queue at least once in the last 7 days |
| 3. | I was seated less than 2 metres away from someone who is not part of my household in a restaurant/cafe/bar at least once in the last 7 days |
| 4. | I have been in a social gathering with more than 6 people who are not part of my household at least once in the last 7 days |
| 5. | I have been in a busy shop/market with no restrictions on number of customers at least once in the last 7 days |
| 6. | I participated in an indoor activity with more than 6 people who are not part of my household at least once in the last 7 days |
| 7. | I have been in a shop/market where one or more of the staff did not wear a mask at least once in the last 7 days |
| 8. | I had an interaction with someone experiencing high body temperature, persistent cough or loss of taste/smell at least once in the last 7 days |

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# Study 2 – Link with theory

Please try to remember how many times you were in the following situation:

**I was seated less than 2 metres away from someone who is not part of my household in a restaurant/cafe/bar at least once in the last 7 days.**

| True | False |
|------|-------|
| (picked by 44% last week) | (picked by 56% last week) |

Submit

If you report True, bonus = % True this week - % True last week (=44)

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Analogous to PPM:

- $v$ = Proportion of "True" this week
- $p = E[\omega] = 0.44$ (common prior on True)

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| True | False |
|---|---|
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- Mental cost of remembering.
- Shame of answering "True" or lying.

# Study 2 - Experimental conditions

Weekly survey in the UK, 3 weeks, November 2020

3 Experimental conditions

Control-1 (flat fee)

**I may have stood less than 2 metres away from the person in front in a queue at least once in the last 7 days.**

| True | False |
|------|-------|

Weekly survey in the UK, 3 weeks, November 2020

3 Experimental conditions

Control-1 (flat fee)

| I may have stood less than 2 metres away from the person in front in a queue at least once in the last 7 days. | |
|---|---|
| True | False |

Treatment (PPM incentives), Control-2 (flat fee)*

| True (picked by 65% last week) | False (picked by 35% last week) |
|---|---|

* tests the effect of just showing the last week's %s.

# Study 2 - Marginal effects, Pr(Response = "True")

|              | (week 2)  |          | (week 3)  |          |
|--------------|-----------|----------|-----------|----------|
|              | (1)       | (2)      | (3)       | (4)      |
| (Intercept)  |           |          |           |          |
|              |           |          |           |          |
| Control-2    | 0.05      | 0.04     | −0.01     | −0.00    |
|              | (0.04)    | (0.04)   | (0.04)    | (0.04)   |
| PPM          | 0.11***   | 0.10**   | 0.08*     | 0.08*    |
|              | (0.03)    | (0.03)   | (0.04)    | (0.04)   |
| Age          |           | −0.00    |           | −0.00    |
|              |           | (0.00)   |           | (0.00)   |
| Female?      |           | 0.02     |           | −0.02    |
|              |           | (0.03)   |           | (0.03)   |
| UK citizen?  |           | −0.00    |           | 0.03     |
|              |           | (0.03)   |           | (0.04)   |
| Num. obs.    | 1259      | 1259     | 1279      | 1279     |

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{+}p < 0.1$

**Higher rate of self-reported unsafe behavior in the PPM treatment.**

Contribution

# Literature

Mechanism design literature: Explored ways to reveal private signals (Crémer and McLean, 1988).

Sender-Receiver games, Bayesian Elicitation (Whitmeyer, 2019)

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Mechanism design literature: Explored ways to reveal private signals (Crémer and McLean, 1988).

Sender-Receiver games, Bayesian Elicitation (Whitmeyer, 2019)

Peer prediction method (Miller et al., 2005): similar framework, but

- The complete prior must be known
- Scoring is not transparent

Bayesian truth-serum (Prelec, 2004) and follow-ups:

- Detail-free (implementer needs less), but more demanding from respondents (answer + prediction)

**Usually, costly effort to acquire signal not modelled.**

Peer prediction markets: Transparent, easy to implement.

Peer prediction markets: Transparent, easy to implement.

Strong assumptions, but same as or weaker than in the literature.

Limitations: Binary questions only, multiple equilibria.

# Thank you!

https://cempeker.github.io/

# References

Crémer, J. and McLean, R. P. (1988). Full extraction of the surplus in bayesian and dominant strategy auctions. *Econometrica: Journal of the Econometric Society*, pages 1247–1257.

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