Confirming cognitive contextuality

Violation of the Leggett-Garg inequality and demonstration of cognitive hysteresis in perceiving cup-like objects

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Contextuality

(Khrennikov, 2022)

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Contextuality

- The values of an observable are not the objective properties of the systems.
- They are created in the process of the complex interaction between the systems prepared for measurements and the apparatus used for measurement.
- An outcome of any observable is composed of the contributions of a system and a measurement device.

(Khrennikov, 2022)

Incompatibility

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- There is no reason to expect that all experimental contexts can be combined with each other and all observables can be measured jointly; Thus, some observables can be incompatible.
- The Heisenberg uncertainty principle implies that the position and momentum observables are incompatible.

(Khrennikov, 2022)

Joint measurement contextuality

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Joint measurement contextuality

- Contextuality means that random variables recorded under mutually incompatible conditions cannot be join together into a single system of jointly distributed random variables,
- provided one assumes that their identity across different conditions changes as little as possibly allowed by direct cross-influences (equivalently, by observed deviations from marginal selectivity).

(Kujala & Dzhafarov, 2016)

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Cyclic systems, conteXts and conteNts

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- Cyclic systems have played a prominent role in contextuality studies (Araújo et al., 2013; Dzhafarov & Kujala, 2016).

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- Cyclic systems have played a prominent role in contextuality studies (Araújo et al., 2013; Dzhafarov & Kujala, 2016).
- The c-c matrix for a cyclic system of an arbitrary rank n

R_1^1	R_2^1	$\cdot$	$\cdot$	$\cdots$	$\cdot$	$\cdot$	C^1
$\cdot$	R_2^2	R_3^2	$\cdot$	$\cdots$	$\cdot$	$\cdot$	C^2
$\cdot$	$\cdot$	R_3^3	R_4^3	$\cdots$	$\cdot$	$\cdot$	C^3
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$
$\cdot$	$\cdot$	$\cdot$	$\cdot$	$\cdots$	R_{n-1}^{n-1}	R_n^{n-1}	C^{n-1}
R_1^n	$\cdot$	$\cdot$	$\cdot$	$\cdots$	$\cdot$	R_n^n	C^n
Q_1	Q_2	Q_3	Q_4	$\cdots$	Q_{n-1}	Q_n	$\mathscr{R}_n$

(Dzhafarov & Kujala, 2016)

Cyclic system of rank 5

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- The c-c matrix for a cyclic system of rank 5

R_1^1	R_2^1	$\cdot$	$\cdot$	$\cdot$	C^1
$\cdot$	R_2^2	R_3^2	$\cdot$	$\cdot$	C^2
$\cdot$	$\cdot$	R_3^3	R_4^3	$\cdot$	C^3
$\cdot$	$\cdot$	$\cdot$	R_4^4	R_5^4	C^4
R_1^5	$\cdot$	$\cdot$	$\cdot$	R_5^5	C^5
Q_1	Q_2	Q_3	Q_4	Q_5	$\mathscr{R}_5$

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$\cdot$	$\cdot$	$\cdot$	R_4^4	R_5^4	C^4
R_1^5	$\cdot$	$\cdot$	$\cdot$	R_5^5	C^5
Q_1	Q_2	Q_3	Q_4	Q_5	$\mathscr{R}_5$

- Klyachko-Can-Binicioglu-Shumovsky experiment (Klyachko et al., 2008; Lapkiewicz et al., 2011).

Cyclic system of rank 4

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- The c-c matrix for a cyclic system of rank 4

R_1^1	R_2^1	$\cdot$	$\cdot$	C^1
$\cdot$	R_2^2	R_3^2	$\cdot$	C^2
$\cdot$	$\cdot$	R_3^3	R_4^3	C^3
R_1^1	$\cdot$	$\cdot$	R_4^3	C^4
Q_1	Q_2	Q_3	Q_4	$\mathscr{R}_4$

Cyclic system of rank 4

- The c-c matrix for a cyclic system of rank 4

R_1^1	R_2^1	$\cdot$	$\cdot$	C^1
$\cdot$	R_2^2	R_3^2	$\cdot$	C^2
$\cdot$	$\cdot$	R_3^3	R_4^3	C^3
R_1^1	$\cdot$	$\cdot$	R_4^3	C^4
Q_1	Q_2	Q_3	Q_4	$\mathscr{R}_4$

- Bell's "Alice-Bob" experiments (Bell, 1964, 1966; Clauser et al., 1969; Fine, 1982).

Cyclic system of rank 3

Cyclic system of rank 3

- The c-c matrix for a cyclic system of rank 3

R_1^1	R_2^1	$\cdot$	C^1
$\cdot$	R_2^2	R_3^2	C^2
R_1^3	$\cdot$	R_3^3	C^3
Q_1	Q_2	Q_3	$\mathscr{R}_3$

Cyclic system of rank 3

- The c-c matrix for a cyclic system of rank 3

R_1^1	R_2^1	$\cdot$	C^1
$\cdot$	R_2^2	R_3^2	C^2
R_1^3	$\cdot$	R_3^3	C^3
Q_1	Q_2	Q_3	$\mathscr{R}_3$

- Leggett-Garg experiments (Suppes & Zanotti, 1981; Leggett & Garg, 1985; Kofler & Brukner, 2013; Asano et al., 2014; Bacciagaluppi, 2014)

Cyclic system of rank 2

Cyclic system of rank 2

- The c-c matrix for a cyclic system of rank 2

R_1^1	R_2^1	C^1
R_1^2	R_2^2	C^2
Q_1	Q_2	$\mathscr{R}_2$

Cyclic system of rank 2

- The c-c matrix for a cyclic system of rank 2

R_1^1	R_2^1	C^1
R_1^2	R_2^2	C^2
Q_1	Q_2	$\mathscr{R}_2$

- Question-order effects in decision making (Wang et al., 2014; Busemeyer & Wang, 2018; Huang et al., 2024)

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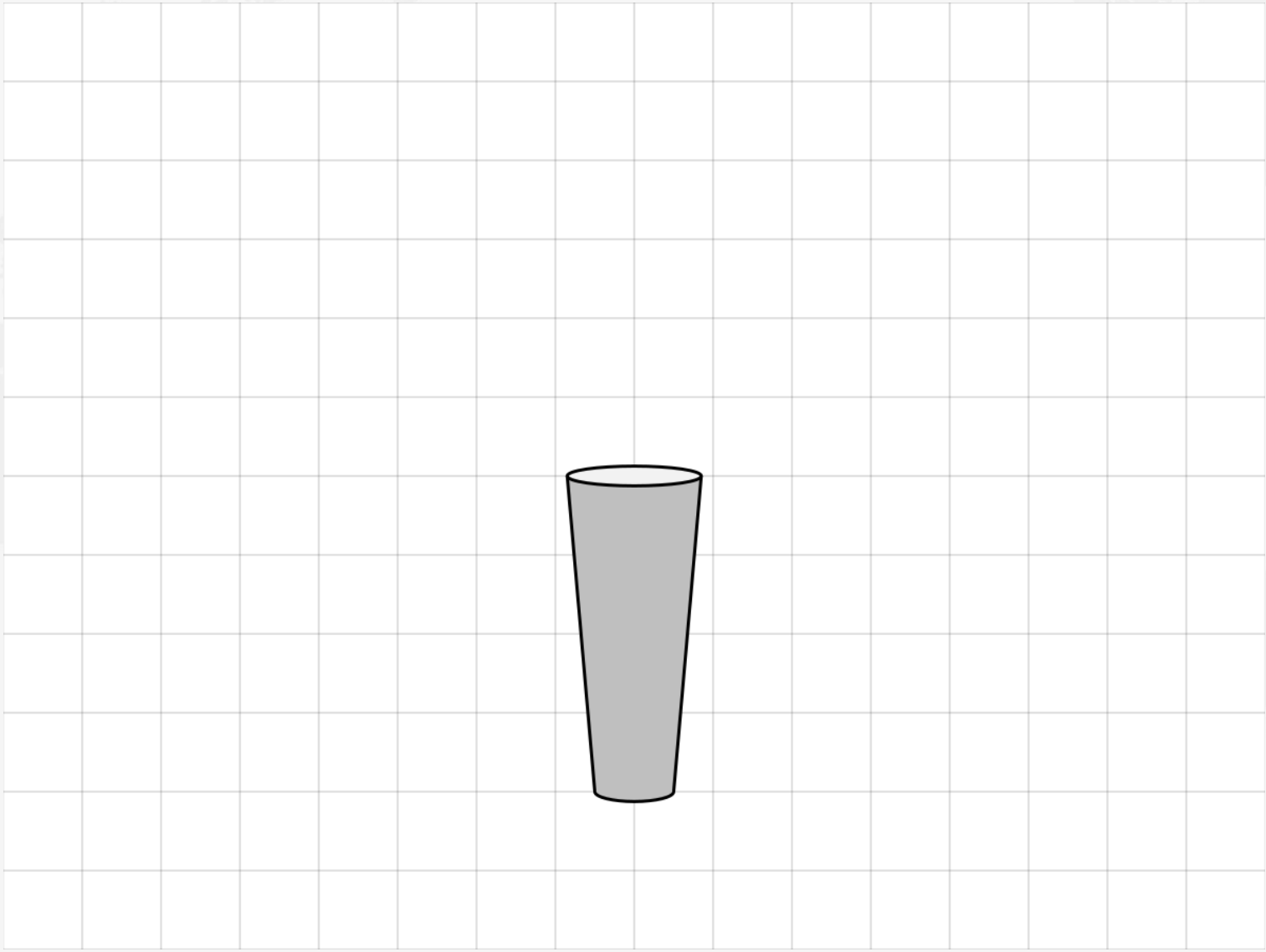
Test stimuli: Cup-like objects



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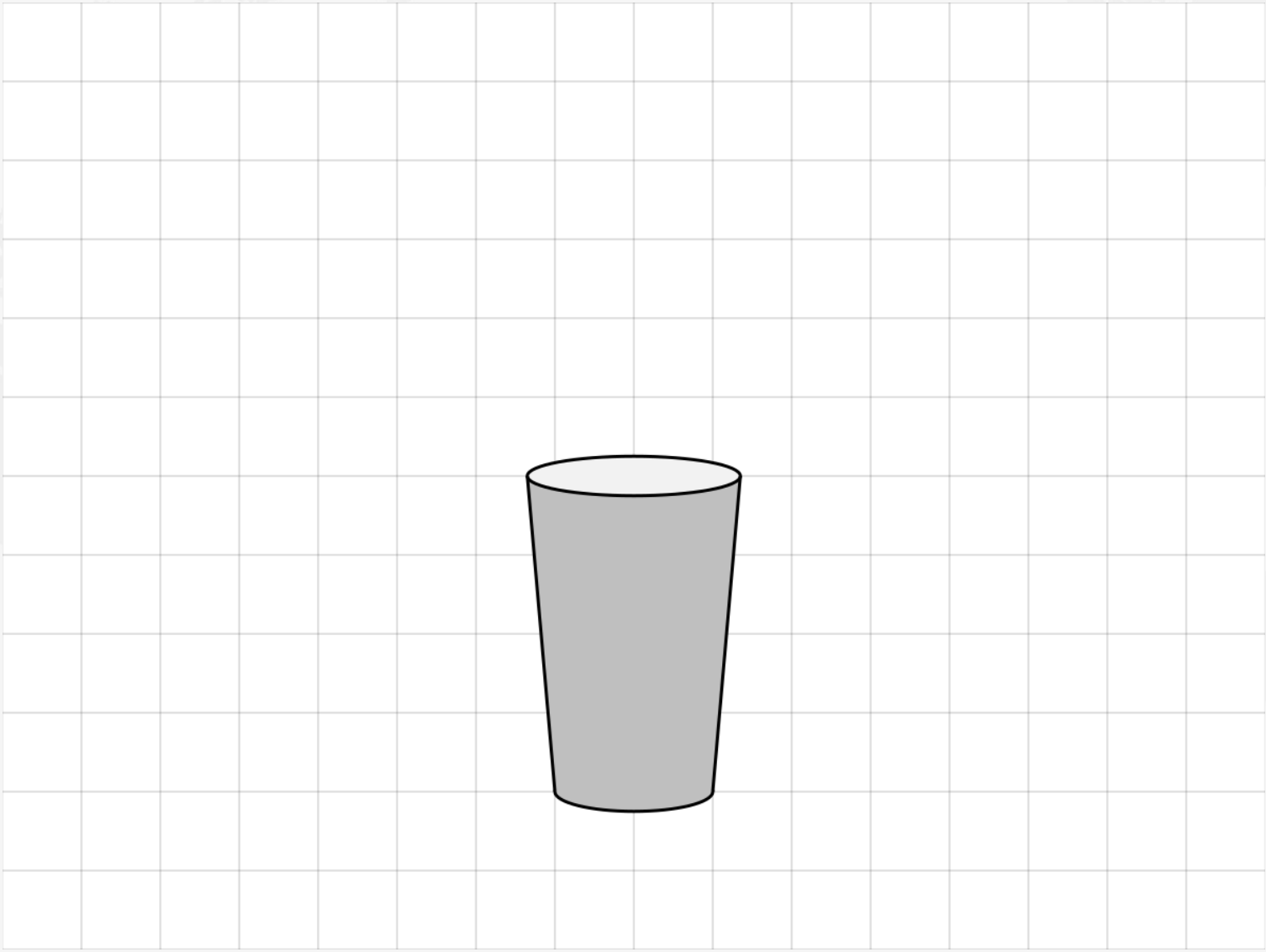
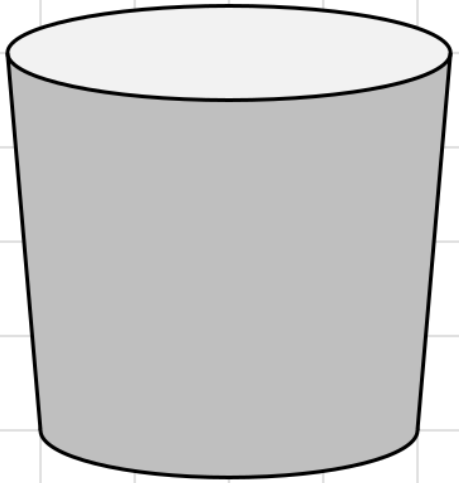


Test stimuli: Cup-like objects



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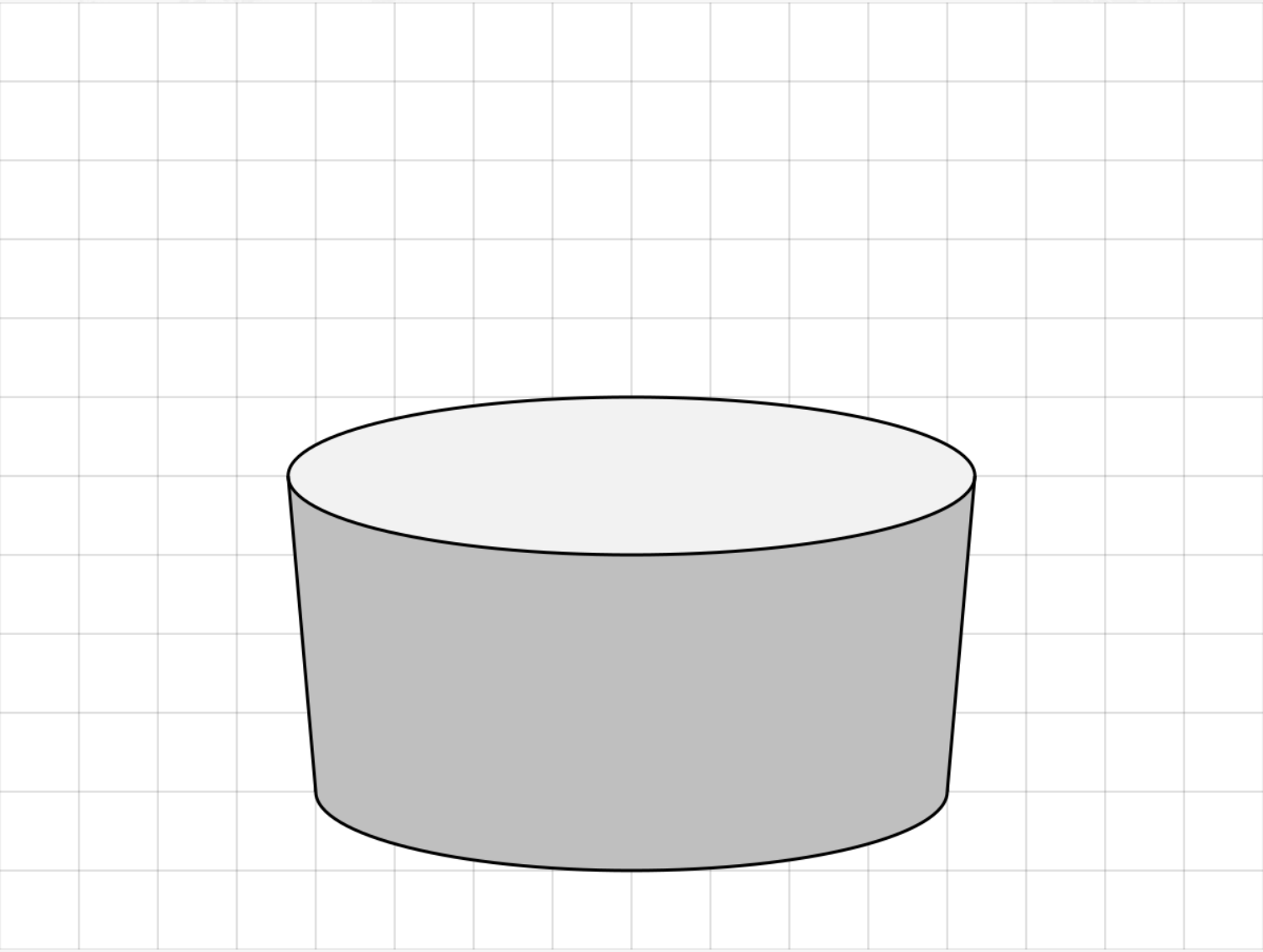

Experimental design

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- Our experiments are rank-3 like systems

R_1^1	$\cdots$	R_i^1	$\cdots$	R_{176}^1	C^1
R_1^2	$\cdots$	R_i^2	$\cdots$	R_{176}^2	C^2
R_1^3	$\cdots$	R_i^3	$\cdots$	R_{176}^3	C^3
Q_1	$\cdots$	Q_i	$\cdots$	Q_{176}	$\mathscr{R}_3$
$w_1 = .50$	$\cdots$	$w_i = .50+$ $.02 * (i-1)$	$\cdots$	$w_{176} = 4.0$	

Experimental design: Cyclic system of rank 3

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- Given any $i < j < k$, we can obtain a cyclic system of rank 3

R_i^1	R_j^1	R_k^1	C^1
R_i^2	R_j^2	R_k^2	C^2
R_i^3	R_j^3	R_k^3	C^3
Q_i	Q_j	Q_k	$\mathscr{R}_3$
w_i	w_j	w_k	$i < j < k$

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R_i^3	R_j^3	R_k^3	C^3
Q_i	Q_j	Q_k	$\mathscr{R}_3$
w_i	w_j	w_k	$i < j < k$

- The three variables in the same context are jointly distributed: $P^c(R_i^c, R_j^c, R_k^c)$ for $c \in \{C^1, C^2, C^3\}$

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$$P^c(R_i^c, R_j^c) = \sum_{R_k^c = \pm 1} P^c(R_i^c, R_j^c, R_k^c) \tag{1}$$

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- We also have

$$P^c(R_i^c) = \sum_{R_j^c = \pm 1} P^c(R_i^c, R_j^c) = \sum_{R_k^c = \pm 1} P^c(R_i^c, R_k^c) \tag{2}$$

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- Finally, we have

$$1 = \sum_{R_i^c = \pm 1} P^c(R_i^c) \tag{3}$$

Experimental design: Cyclic system of rank 3

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- If they are jointly distribtued, the correlation functions between two random variables R_i^c and R_j^c are

$$\begin{aligned} C_{ij}^c =& P^c(R_i^c = 1, R_j^c = 1) + P^c(R_i^c = -1, R_j^c = -1) \\ & - P^c(R_i^c = 1, R_j^c = -1) - P^c(R_i^c = 1, R_j^c = -1) \\ =& 2[P^c(R_i^c = 1, R_j^c = 1) + P^c(R_i^c = -1, R_j^c = -1)] - 1 \end{aligned} \tag{4}$$

Leggett–Garg inequality

$$
\begin{aligned}
K =& C_{ij}^c + C_{jk}^c - C_{ik}^c \\
=& \{2[P(R_i^c = 1, R_j^c = 1) + P(R_i^c = -1, R_j^c = -1)] - 1\} + \{2[P(R_j^c = 1, R_k^c = 1) + P(R_j^c = -1, R_k^c = -1)] - 1\} - \\
& \{2[P(R_i^c = 1, R_k^c = 1) + P(R_i^c = -1, R_k^c = -1)] - 1\} \\
=& \{2[P(R_i^c = 1, R_j^c = 1, R_k^c = 1) + P(R_i^c = 1, R_j^c = 1, R_k^c = -1) + P(R_i^c = -1, R_j^c = -1, R_k^c = 1) + P(R_i^c = -1, R_j^c = -1, R_k^c = -1)] - 1\} + \\
& \{2[P(R_j^c = 1, R_k^c = 1, R_i^c = 1) + P(R_j^c = 1, R_k^c = 1, R_i^c = -1) + P(R_j^c = -1, R_k^c = -1, R_i^c = 1) + P(R_j^c = -1, R_k^c = -1, R_i^c = -1)] - 1\} - \\
& \{2[P(R_i^c = 1, R_k^c = 1, R_j^c = 1) + P(R_i^c = 1, R_k^c = 1, R_j^c = -1) + P(R_i^c = -1, R_k^c = -1, R_j^c = 1) + P(R_i^c = -1, R_k^c = -1, R_j^c = -1)] - 1\} \\
=& \{2[P(R_i^c = 1, R_j^c = 1, R_k^c = 1) + P(R_i^c = 1, R_j^c = 1, R_k^c = -1) + P(R_i^c = -1, R_j^c = -1, R_k^c = 1) + P(R_i^c = -1, R_j^c = -1, R_k^c = -1)] - 1\} + \\
& \{2[P(R_i^c = 1, R_j^c = 1, R_k^c = 1) + P(R_i^c = -1, R_j^c = 1, R_k^c = 1) + P(R_i^c = 1, R_j^c = -1, R_k^c = -1) + P(R_i^c = -1, R_j^c = -1, R_k^c = -1)] - 1\} - \\
& \{2[P(R_i^c = 1, R_j^c = 1, R_k^c = 1) + P(R_i^c = 1, R_j^c = -1, R_k^c = 1) + P(R_i^c = -1, R_j^c = 1, R_k^c = -1) + P(R_i^c = -1, R_j^c = -1, R_k^c = -1)] - 1\} \\
=& \{2P(R_i^c = 1, R_j^c = 1, R_k^c = 1) + 2P(R_i^c = 1, R_j^c = 1, R_k^c = -1) + 2P(R_i^c = -1, R_j^c = -1, R_k^c = 1) + 2P(R_i^c = -1, R_j^c = -1, R_k^c = -1) - 1\} + \\
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& \{2P(R_i^c = 1, R_j^c = 1, R_k^c = 1) + 2P(R_i^c = 1, R_j^c = -1, R_k^c = 1) + 2P(R_i^c = -1, R_j^c = 1, R_k^c = -1) + 2P(R_i^c = -1, R_j^c = -1, R_k^c = -1) - 1\} \\
=& \{2P(R_i^c = 1, R_j^c = 1, R_k^c = 1) + 2P(R_i^c = 1, R_j^c = 1, R_k^c = -1) + 2P(R_i^c = -1, R_j^c = -1, R_k^c = 1) + 2P(R_i^c = -1, R_j^c = -1, R_k^c = -1) - 1\} + \\
& \{2P(R_i^c = -1, R_j^c = 1, R_k^c = 1) + 2P(R_i^c = 1, R_j^c = -1, R_k^c = -1)\} - \{2P(R_i^c = 1, R_j^c = -1, R_k^c = 1) + 2P(R_i^c = -1, R_j^c = 1, R_k^c = -1)\} \\
=& + 2P(R_i^c = 1, R_j^c = 1, R_k^c = 1) + 2P(R_i^c = 1, R_j^c = 1, R_k^c = -1) + 2P(R_i^c = -1, R_j^c = -1, R_k^c = 1) + 2P(R_i^c = -1, R_j^c = -1, R_k^c = -1) \\
& + 2P(R_i^c = -1, R_j^c = 1, R_k^c = 1) + 2P(R_i^c = 1, R_j^c = -1, R_k^c = -1) - 2P(R_i^c = 1, R_j^c = -1, R_k^c = 1) - 2P(R_i^c = -1, R_j^c = 1, R_k^c = -1) - 1 \\
=& 2 - 4P(R_i^c = 1, R_j^c = -1, R_k^c = 1) - 4P(R_i^c = -1, R_j^c = 1, R_k^c = -1) - 1 \\
=& 1 - 4\{P(R_i^c = 1, R_j^c = -1, R_k^c = 1) + P(R_i^c = -1, R_j^c = 1, R_k^c = -1)\} \\
\leq& 1
\end{aligned}
$$

Experimental design: Cyclic system of rank 3

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- If there is no contextuality, i.e., random variables do not depend on experimental contexts, the three variables $(R_i^{c1}, R_j^{c2}, R_k^{c3})$ from different contexts could still be jointly distributed.

R_i^1	R_j^1	$\cdot$	C^1
$\cdot$	R_j^2	R_k^2	C^2
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- The Leggett–Garg inequality should still hold:

$$K = C_{ij}^{c1} + C_{jk}^{c2} - C_{ik}^{c3} \leq 1 \tag{5}$$

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- The Leggett–Garg inequality should still hold:

$$K = C_{ij}^{c1} + C_{jk}^{c2} - C_{ik}^{c3} \leq 1 \tag{5}$$

- If Leggett–Garg inequality is violated, then the joint measurement contextuality occurs.

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Physical contexts

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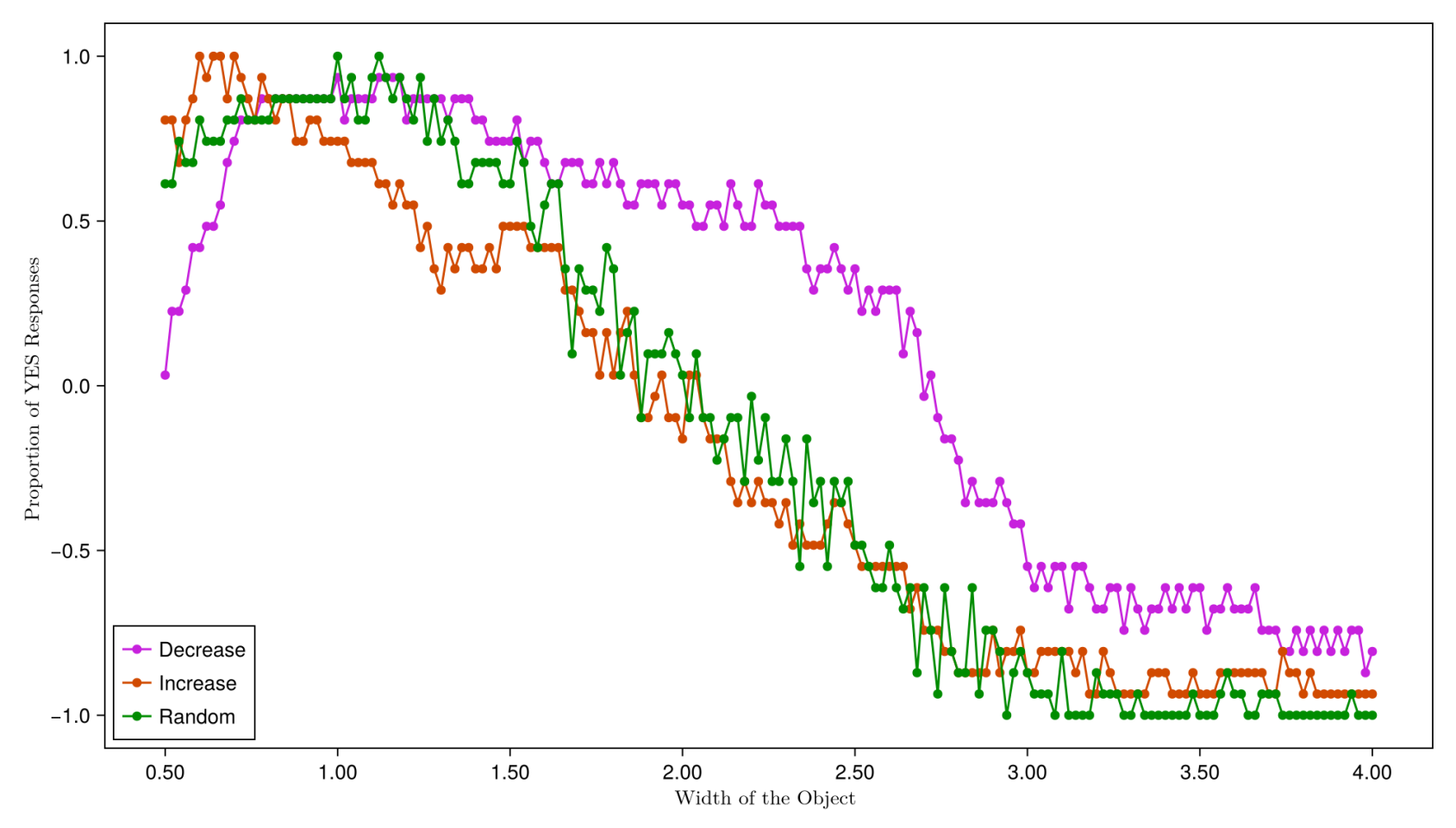
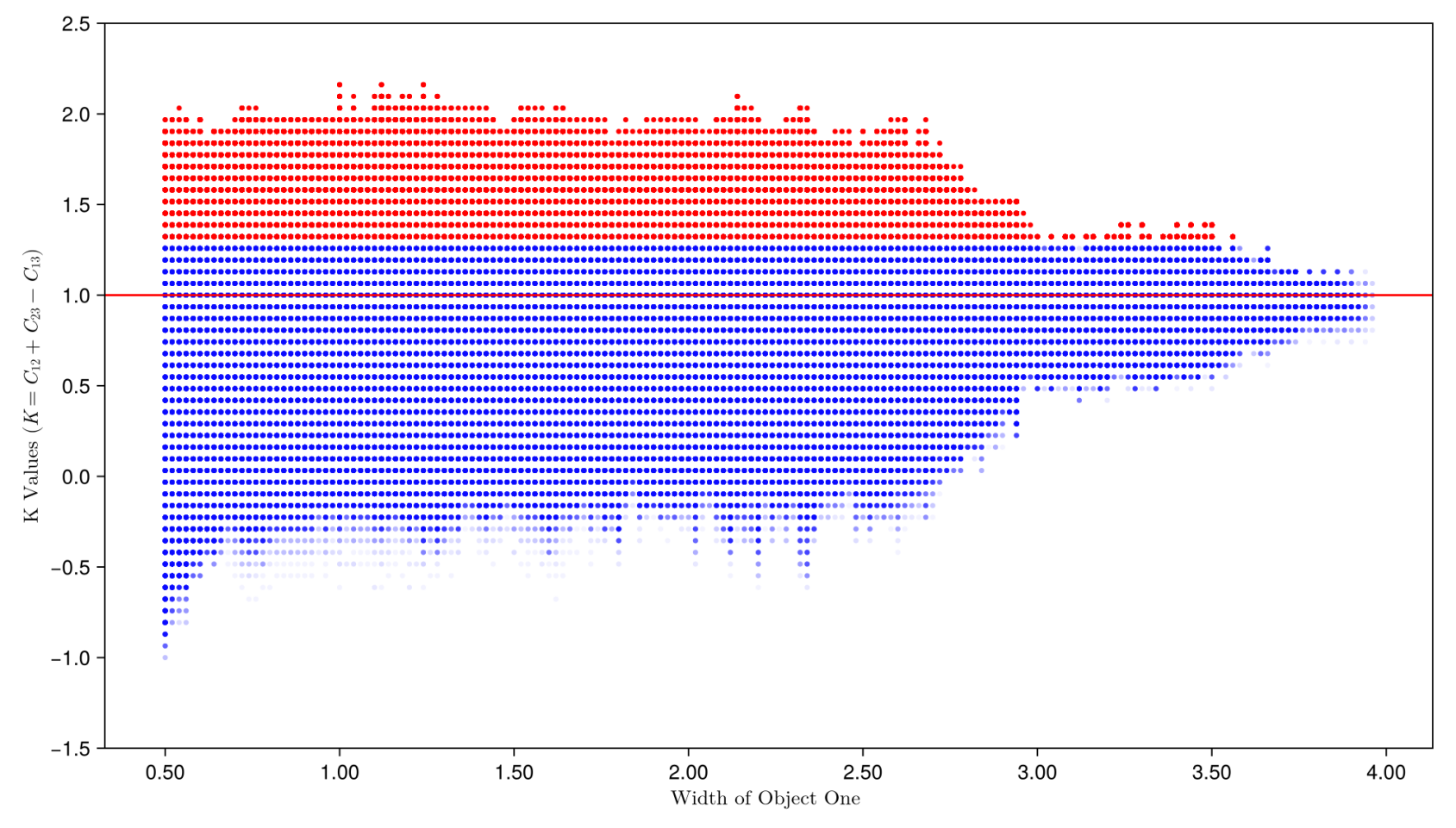
Physical contexts

- The social context was kept “neutral”: Participants are simply asked to judge whether the object is a “cup” or not.
- C^1: Decrease order
- C^2: Increase order
- C^3: Random order

Descriptive results



Statistical analyses



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Social contexts

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- The physical context was kept fixed: Participants are presented the test stimuli in a pseudo-random order and are asked to imagine that they are in the social context given and are asked to judge whether the object is a cup or not.

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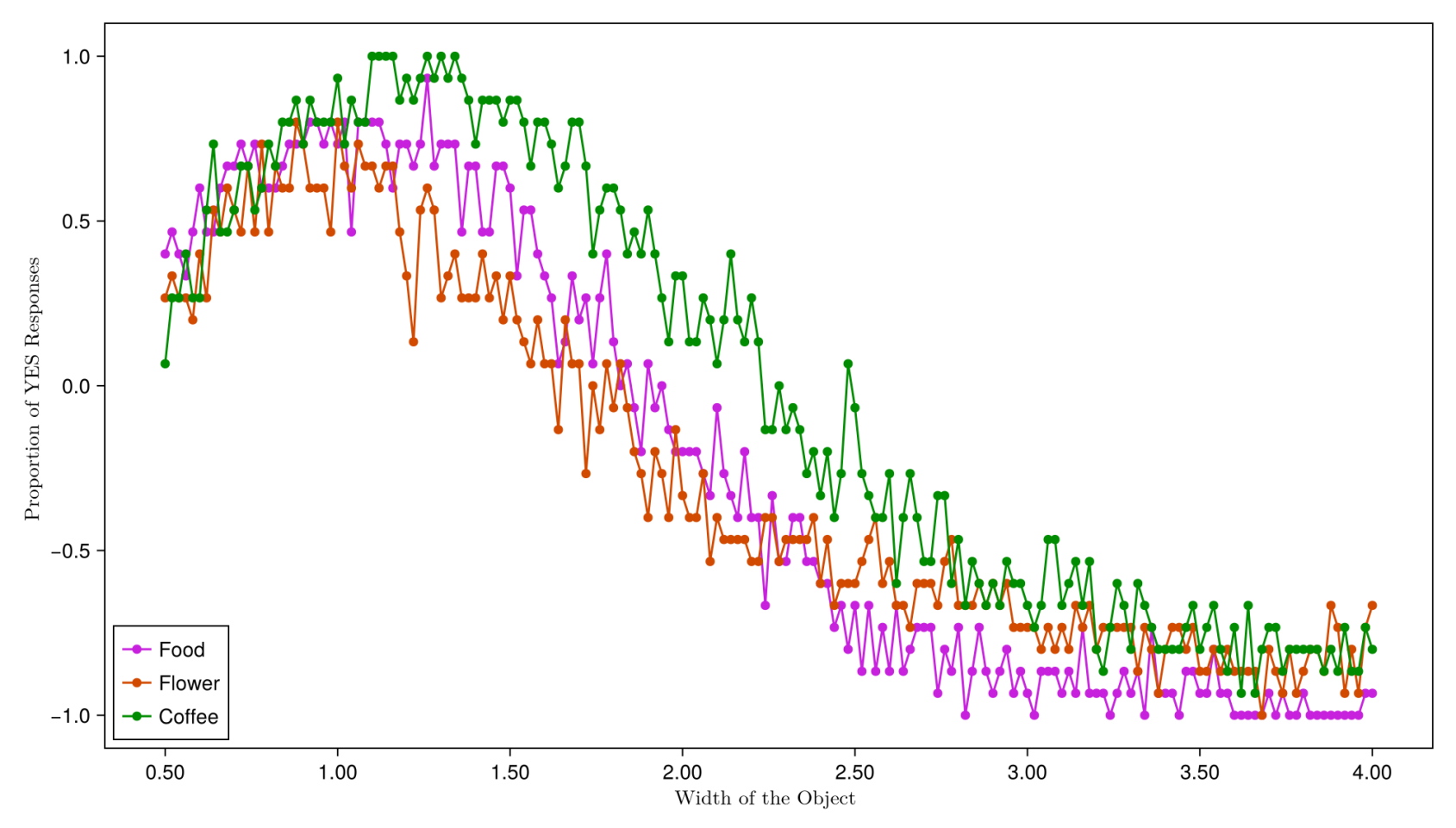
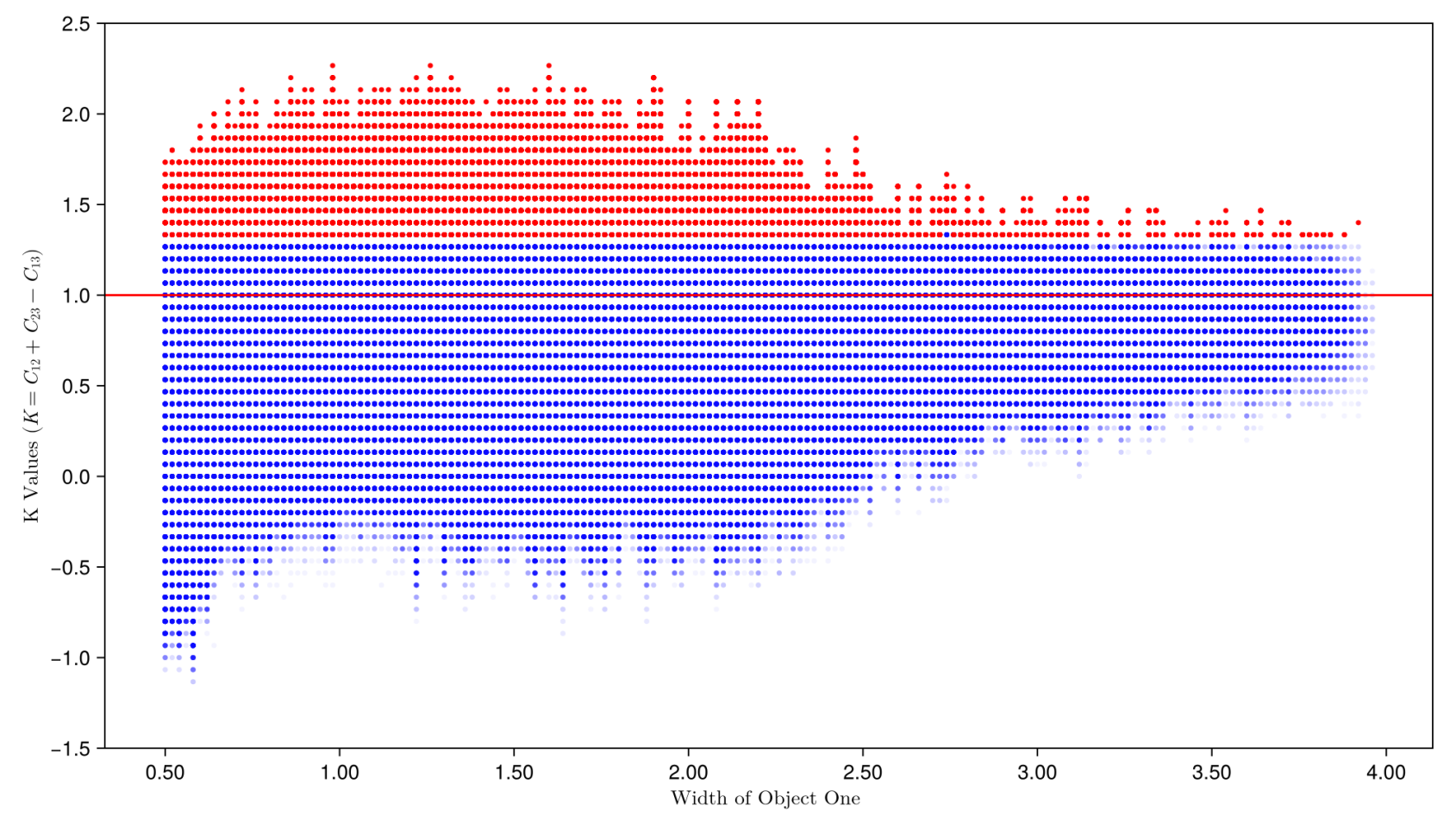
- C^2: food context, participants are asked to imagine that they came to dinner at someone's house and saw this object sitting on the dinner table, filled with rice;
- C^3: flower context, participants are asked to conceive of each of these objects standing on a shelf, each with cut flowers in it.

Descriptive results



Statistical analyses



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Problems to be resolved

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- Signaling

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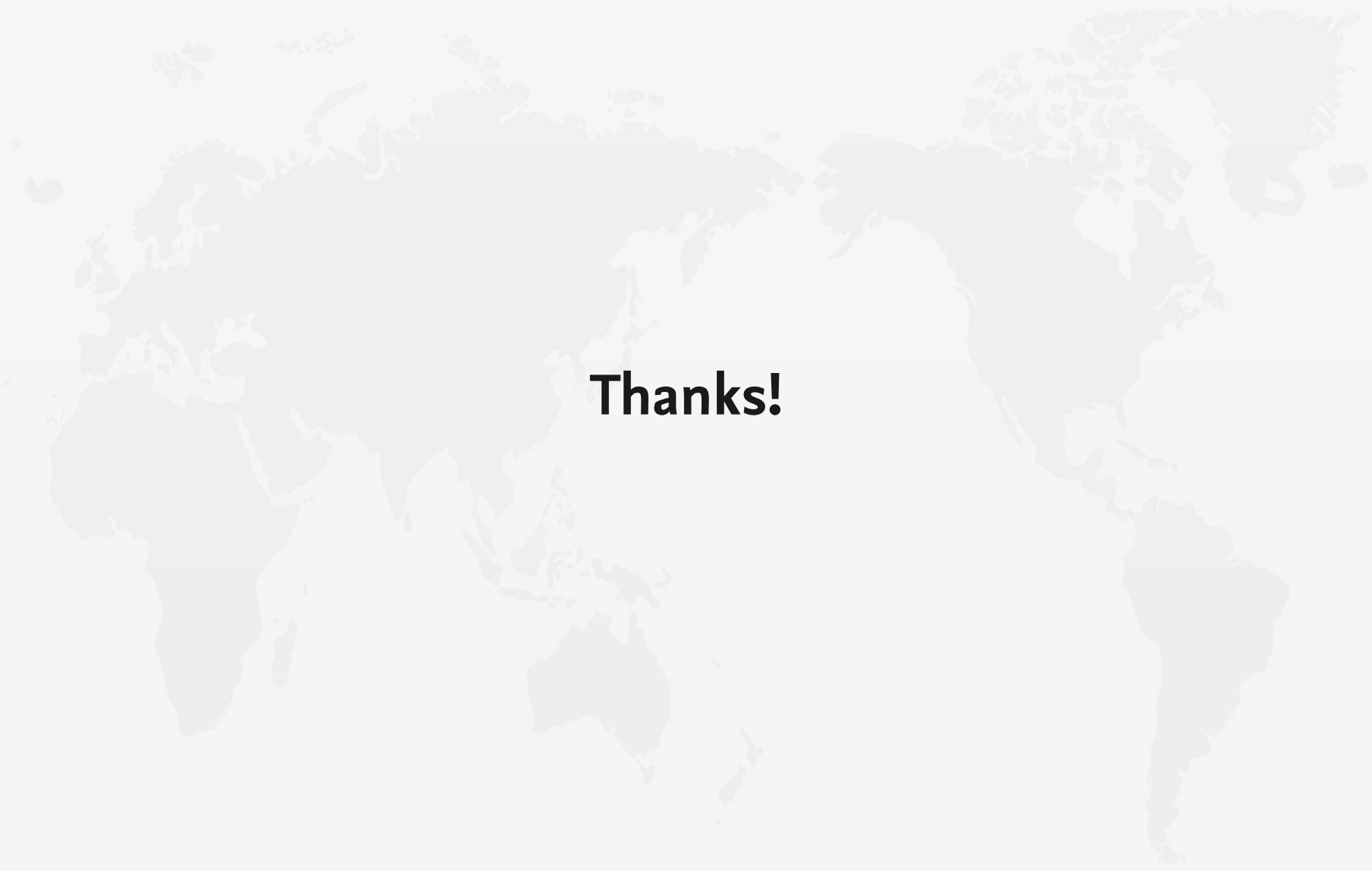
- Signaling
- To compare different formalization



Thanks!

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