Cooperation in networks

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Cooperation

"The range and extent to which humans work together make us supreme cooperators [...] our breathtaking ability to cooperate is one of the main reasons we have managed to survive in every ecosystem on Earth."

Nowak, M. (2011). *Supercooperators*.

- Longstanding work on cooperation in many disciplines (biology, economics, sociology, physics, etc.)
- Until recently empirical/experimental work abstracts away from the role of social networks
  - Early work shows no apparent relation between network structure and emergence of cooperation (Cassar, *GEB* 2007; Gracia-Lázaro et al., *PNAS* 2012).
  - Recently Rand et al. (PNAS 2011) and Wang et al. (PNAS 2012) show that *dynamic* networks increase cooperation.

Objectives

- Which aspects of networks and the environment enable dynamic networks to generate high cooperation?
  - Reputational knowledge
  - Social knowledge
  - Strength of links
  - Gradation in strength
  - Uncertainty
  - Dynamicity
- How does the dynamics of network formation leads to high cooperation?

Gallo, E. and Yan, C. The effects of reputational and social knowledge on cooperation. *Proc. Natl. Acad. Sci.* (2015).

Gallo, E., Riyanto, Y. E., Teh, T. and Roy, N. Strong links promote the emergence of cooperative elites, *Sci. Rep.* (2019).

Gallo, E., Riyanto, Y. E., Roy, N. and Teh, T. Cooperation in an uncertain and dynamic world. *Work in progress*.

Set-up

- 1,132 participants in lab and online experiments
- 12 – 13 subjects in each session
- 13 – 28 rounds (depending on experiment) of the following game with 3 stages:
  1. Subjects can propose costless links to any other subjects and can unilaterally remove any of their existing links
  2. Subjects accept/reject link proposals from others
  3. Choose cooperate (A) or defect (B) in the following game where the action applies to all neighbours

	A	B
A	3	–5
B	5	–3

Important design choices

- Payoff structure
  - The only way to produce social surplus is a *C*-*C* link
  - The only way to reduce social surplus (by an equal amount) is a *D*-*D* link
  - Absence of a link and *C*-*D* links lead to no change in social surplus
  - Previous studies have non-negative or negligible negative payoffs $\Rightarrow$ overconnected networks
- Payment
  - Random selection of 12 pairs for payment for each subject, independent of the presence of a link
  - Previous studies pay the cumulative number of points $\Rightarrow$ satisficing

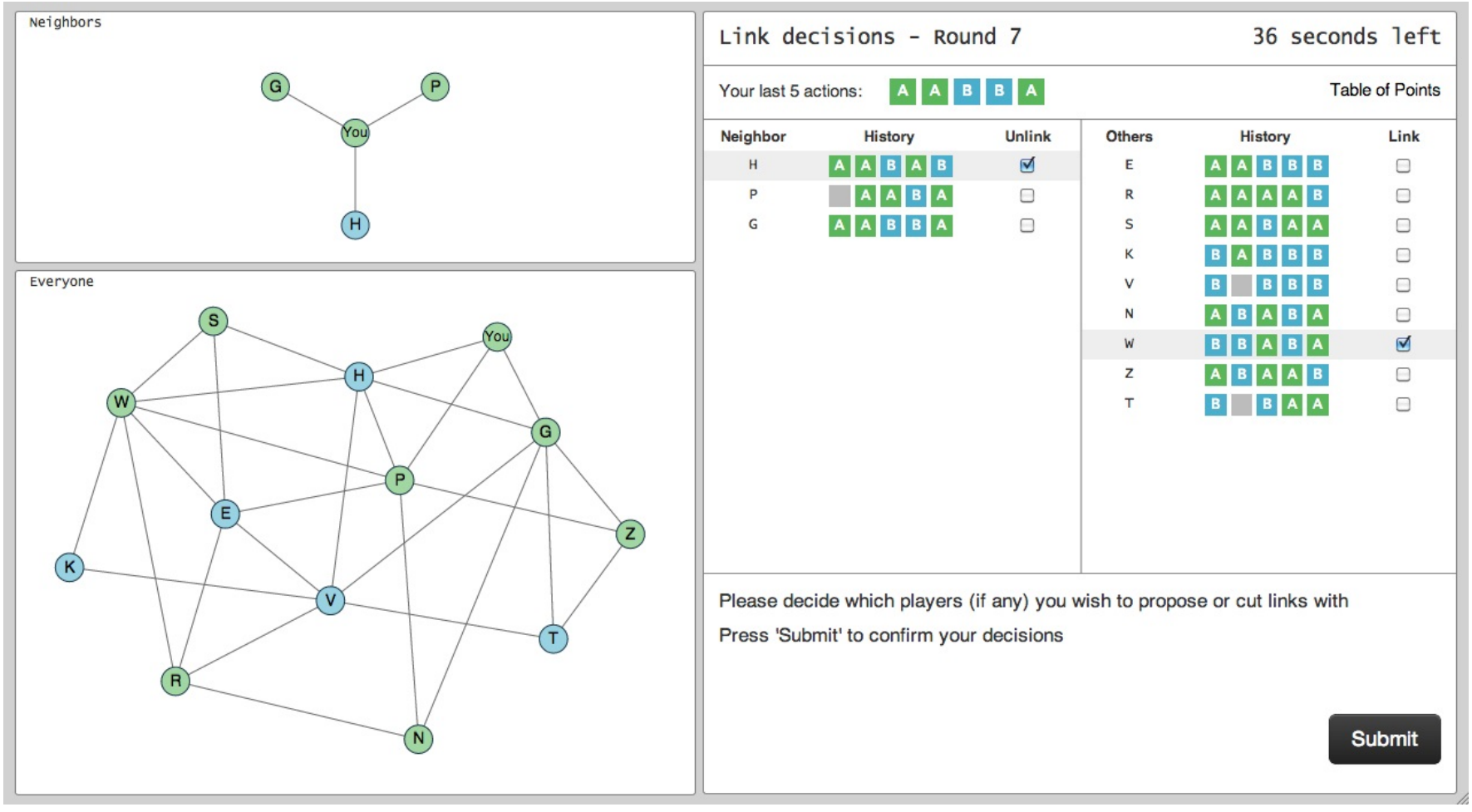
$\Rightarrow$ choice of payoffs and payment method create incentives for the formation of a meaningful network structure and allow the investigation of the association between network structure and cooperation

Study 1 - Gallo and Yan (PNAS, 2015)

- *Reputational knowledge*: information subjects have about the previous actions of other participants
  - Local: last 5 actions chosen by each neighbour
  - Giobal: last 5 actions chosen by each other subject
- *Social knowledge*: information subjects have about the structure of the social network
  - Local: who your neighbours are
  - Giobal: who is connected to whom in the whole network

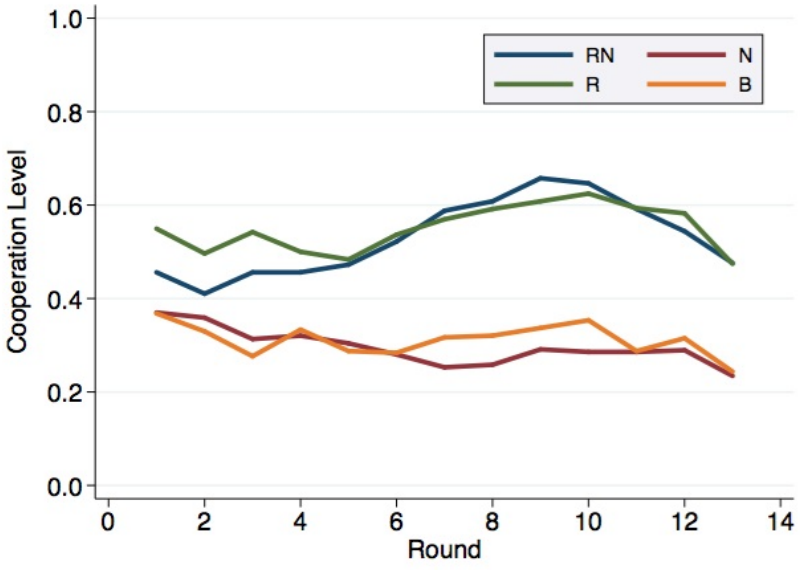
		Social knowledge	
		Local	Global
Reputational knowledge	Local	B	N
	Global	R	RN

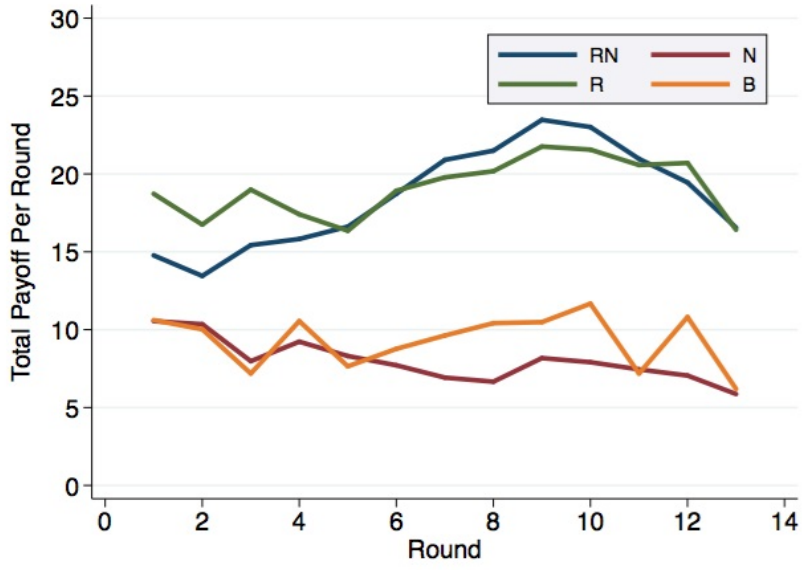
Interface (RN treatment)



Evolution of cooperation and welfare

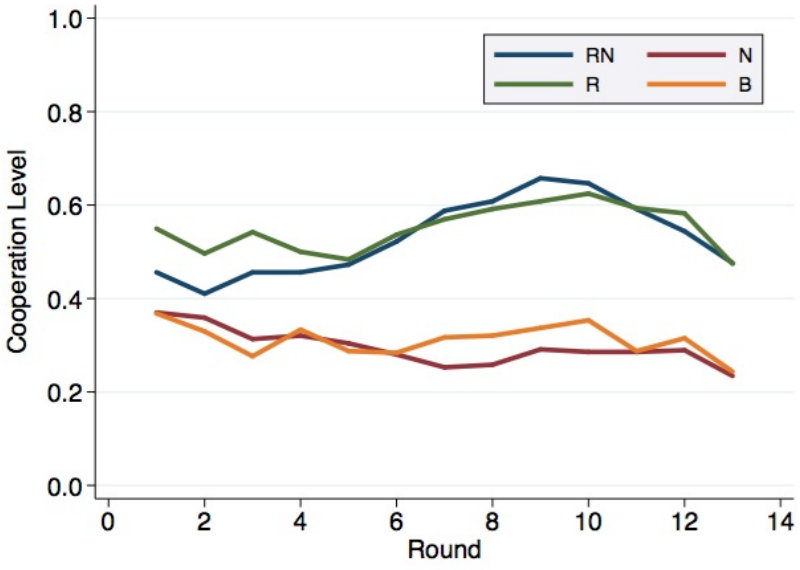
- Cooperation (after round 5) in *RN* is higher than in *B* ($p = 0.036$) and *N* ($p = 0.060$)
- Cooperation (after round 5) in *R* is higher than in *B* ($p = 0.032$) and *N* ($p = 0.036$)

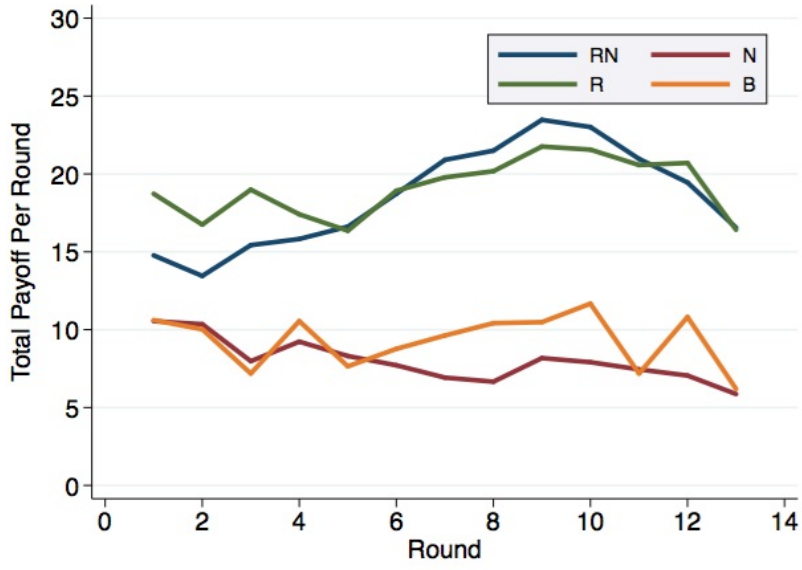




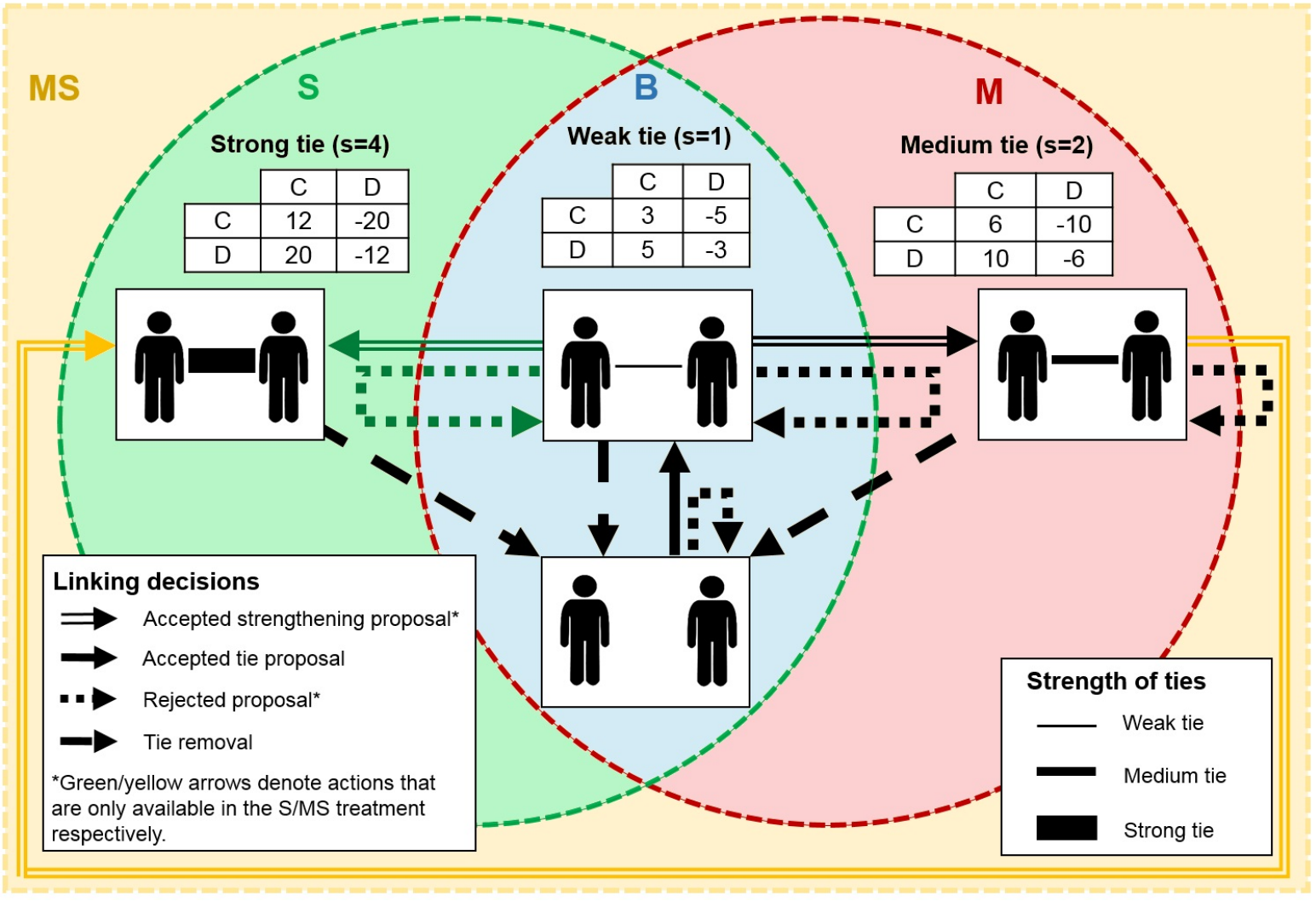
Study 1: Evolution of cooperation and welfare

- Welfare (after round 5) in *RN* is higher than in *B* ($p = 0.041$) and *N* ($p = 0.032$)
- Welfare (after round 5) in *R* is higher than in *B* ($p = 0.031$) and *N* ($p = 0.063$)



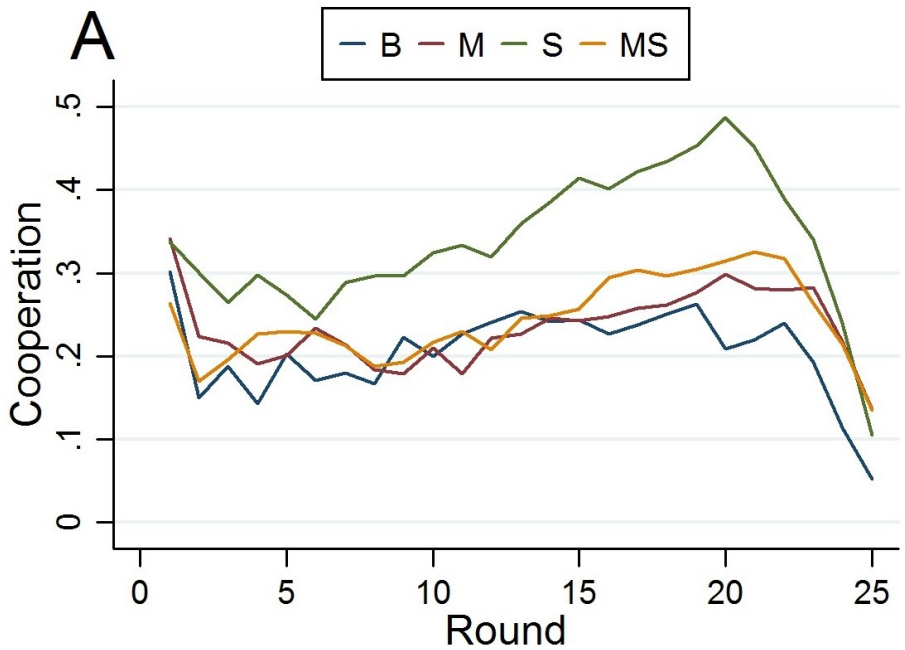


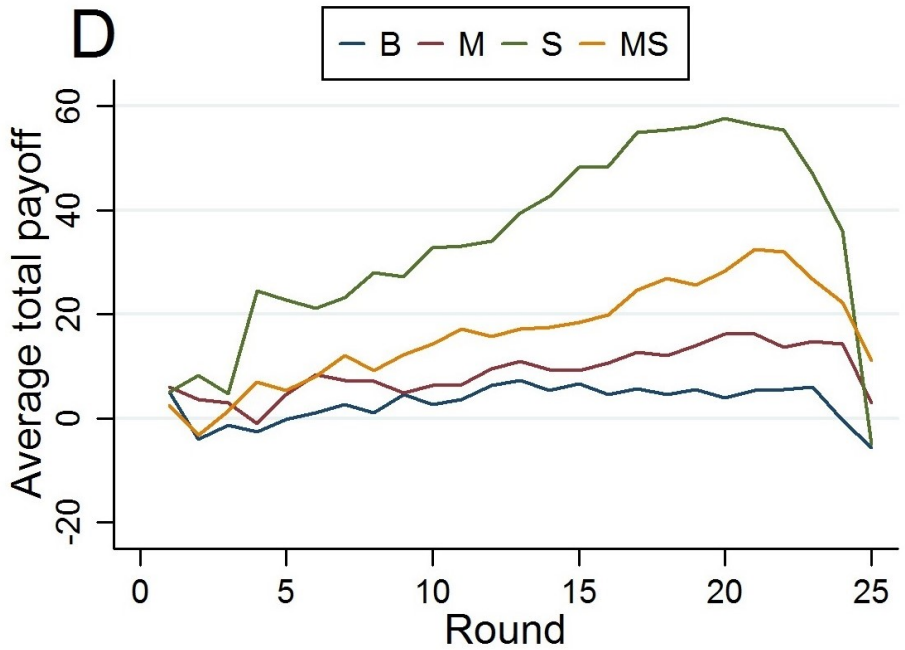
Study 2 - Gallo, Riyanto, Teh and Roy (SciRep, 2019)



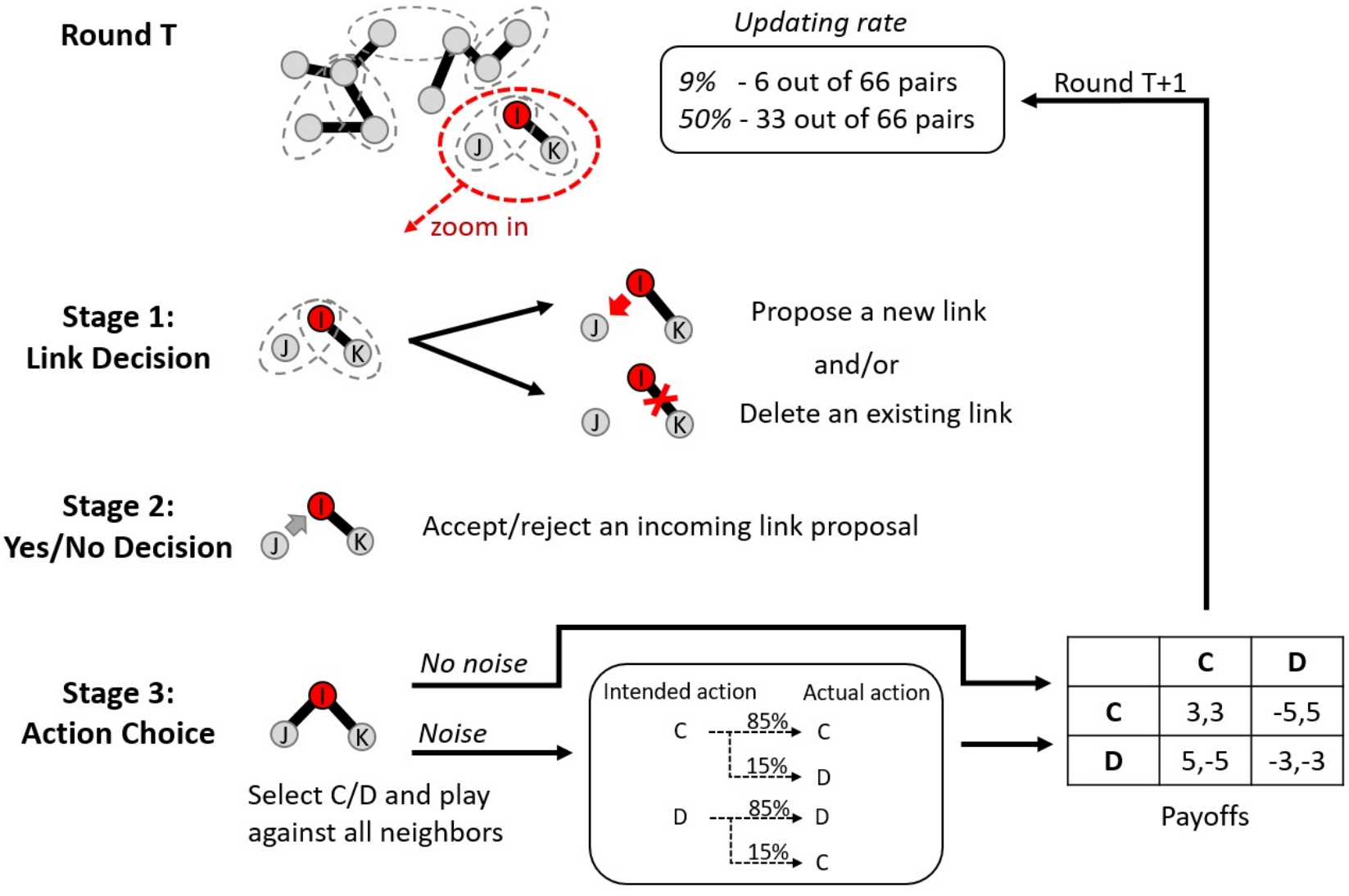
Study 2: Evolution of cooperation and welfare

- Cooperation in *S* is higher than in *B* ($p = 0.05$) and *M* ($p = 0.04$) and qualitatively higher than *MS*
- Welfare in *S* is higher than in *B* ($p = 0.001$), *M* ($p = 0.005$) and *MS* ($p = 0.06$)



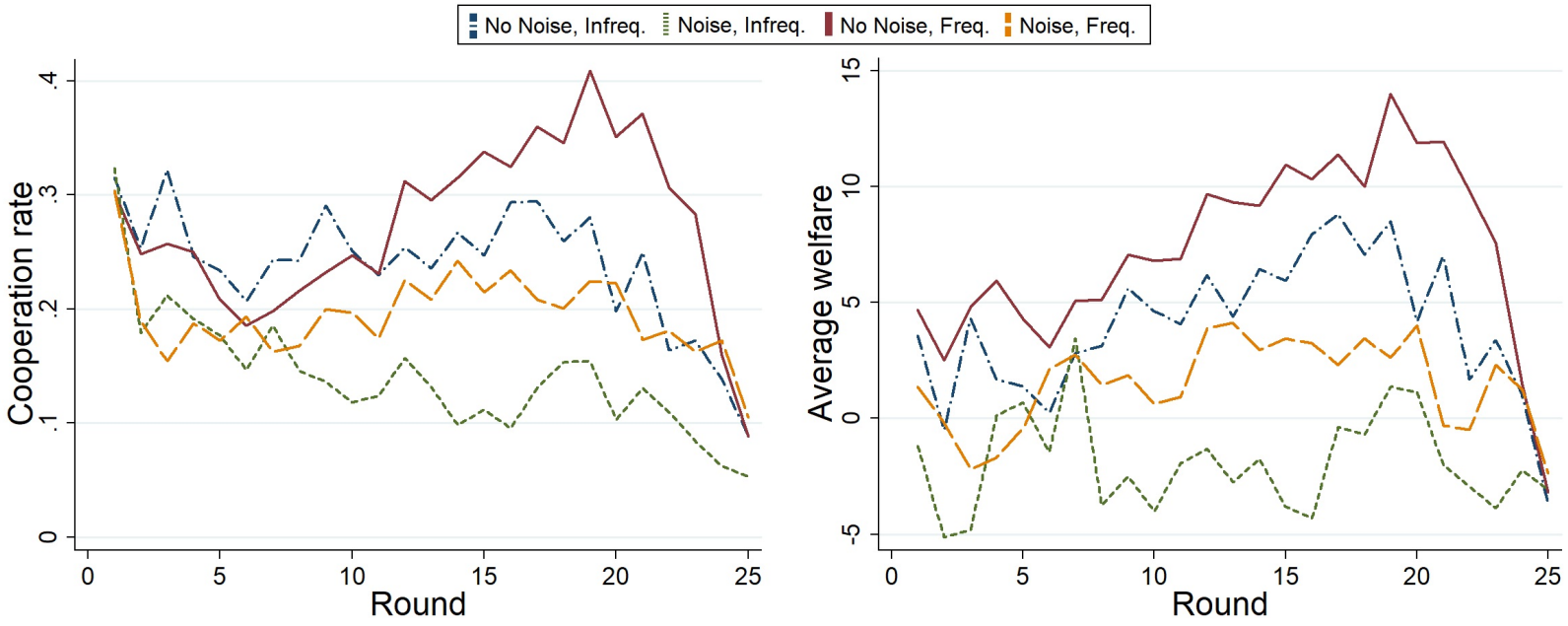


Study 3 - Gallo, Riyanto, Roy and Teh (work in progress)



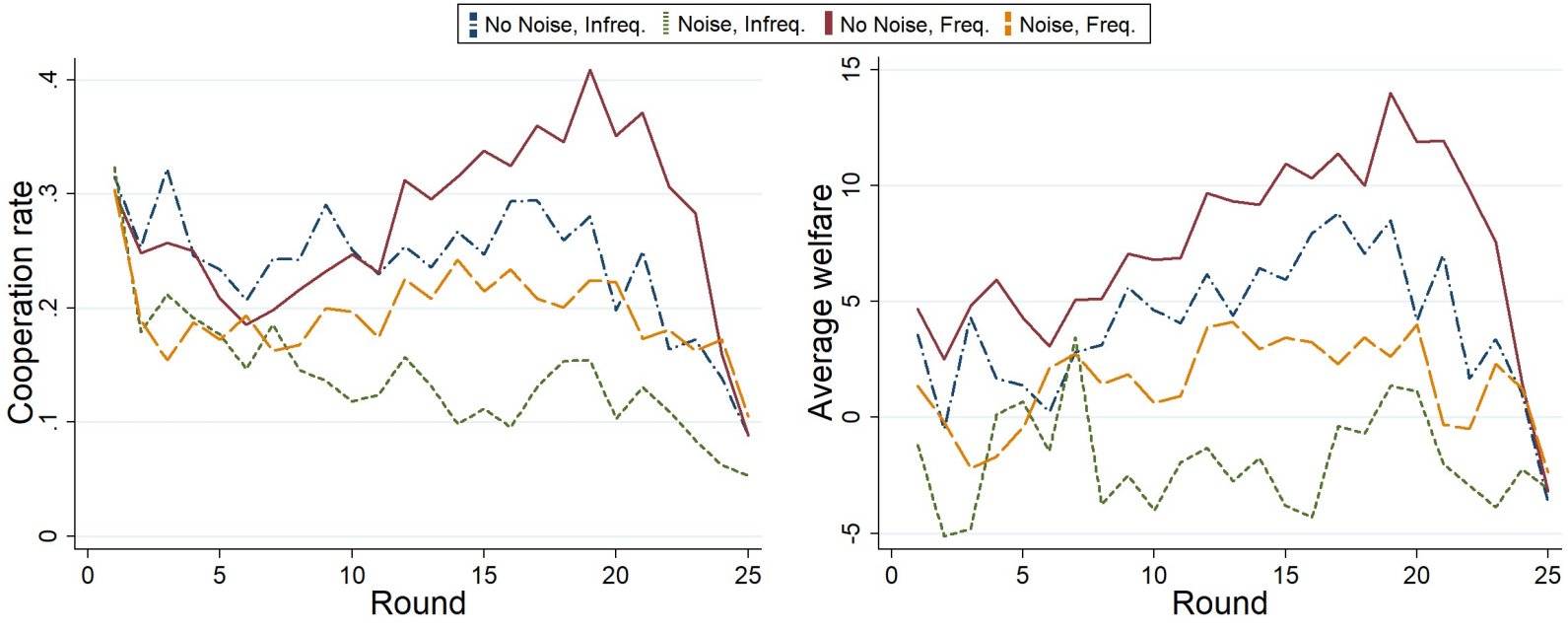
Study 3: Evolution of cooperation and welfare

- Cooperation is higher without reputational uncertainty both in the static ($p = 0.003$) and dynamic ($p = 0.02$) conditions
- Welfare is higher without reputational uncertainty both in the static ($p = 0.02$) and dynamic ($p = 0.03$) conditions



Study 3: Evolution of cooperation and welfare

Holding constant reputational uncertainty, the increase in cooperation/welfare due to dynamic ties is not significant either with (orange vs green) or without (red vs blue) reputational uncertainty.



Determinants of cooperation in dynamic networks

First-order factors in determining high cooperation in *dynamic* networks:

- *Reputational* knowledge about *everyone*
- *(Lack of) gradation in strengthening* of links
- *No uncertainty* in the environment

These factors are second-order or negligible:

- *Social* knowledge about the network (negligible)
- *Strength* of links (negligible)
- How *dynamic* network formation process is (second order)

How to sustain cooperation in dynamic networks

- Basic mechanism at individual level is punishment by cutting links
  - if you defect on me then I unilaterally cut our link and we do not interact anymore
- How do the factors that increase cooperation (and welfare) enhance the effectiveness of the punishment through link cutting?
- *Answer*: they enable the formation of a separate, close-knit community of cooperators that drive the aggregate level of cooperation of the whole group

Recall: Study 1

- *Reputational knowledge*: information subjects have about the previous actions of other participants
  - Local: last 5 actions chosen by each neighbour
  - Giobal: last 5 actions chosen by each other subject
- *Social knowledge*: information subjects have about the structure of the social network
  - Local: who your neighbours are
  - Giobal: who is connected to whom in the whole network

		Social knowledge	
		Local	Global
Reputational knowledge	Local	B	N
	Global	R	RN

Methodology 1: Louvain community detection

- The Louvain community detection algorithm adopts a hierarchical design to greedily partition the network into communities that obtain the highest value of modularity Q:

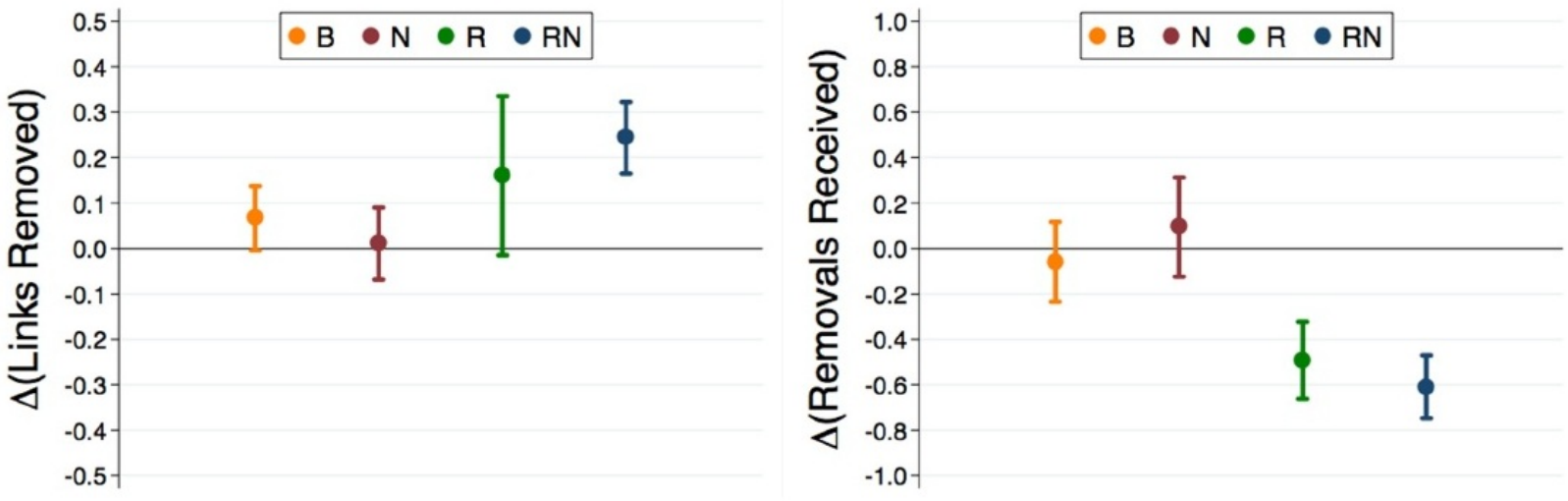
$$Q = \frac{1}{2L} \sum_{C} \left(2l_C - \frac{d_C^2}{2L} \right)$$

  L = total number of links in the network, l_C = number of links in community C, $d_C = \sum_{i \in C} d_i$ is the sum of the degrees d_i for each $i \in C$.
- Steps:
  1. it seeks to optimise the modularity of small partitions of the network locally
  2. it collapses nodes of each community to a single node and constructs a new network using these aggregated nodes
  3. Iterate until it attains a maximum level of modularity
- We rank the communities by size: $C1$ is the largest, $C2$ is the second largest, etc.

Methodology 1: Dynamics of link formation

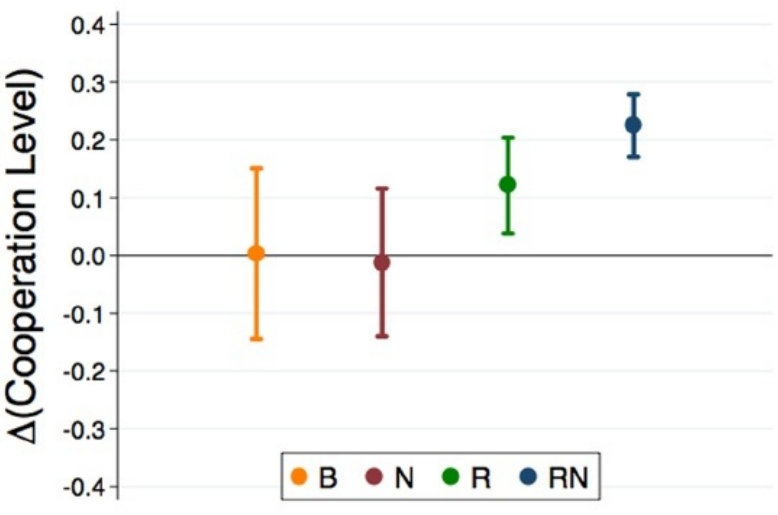
When both global reputational and social knowledge (*RN*) are available, the link removal punishment mechanism is more effective

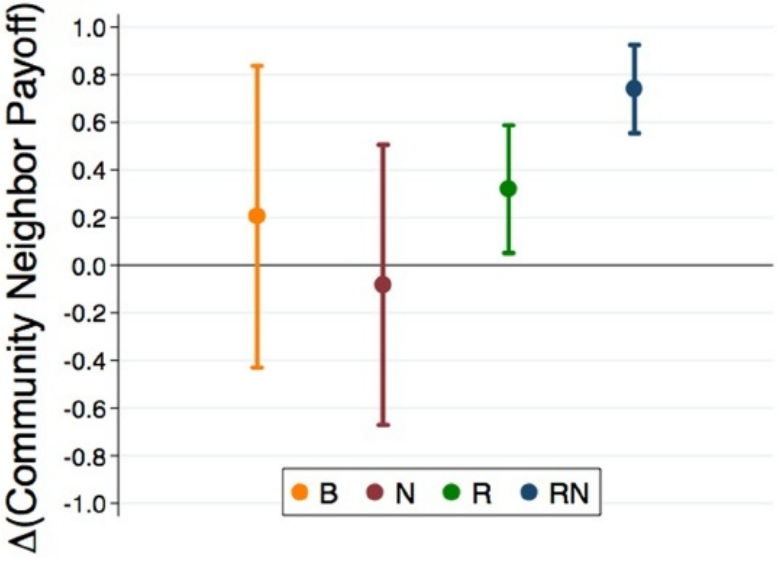
- In *RN* members of *C*1 remove more links than members of *C*2 ($p = 0.018$)
- In *RN* members of *C*2 have more links removed than members of *C*1 ($p = 0.002$)



Methodology 1: A large community of cooperators

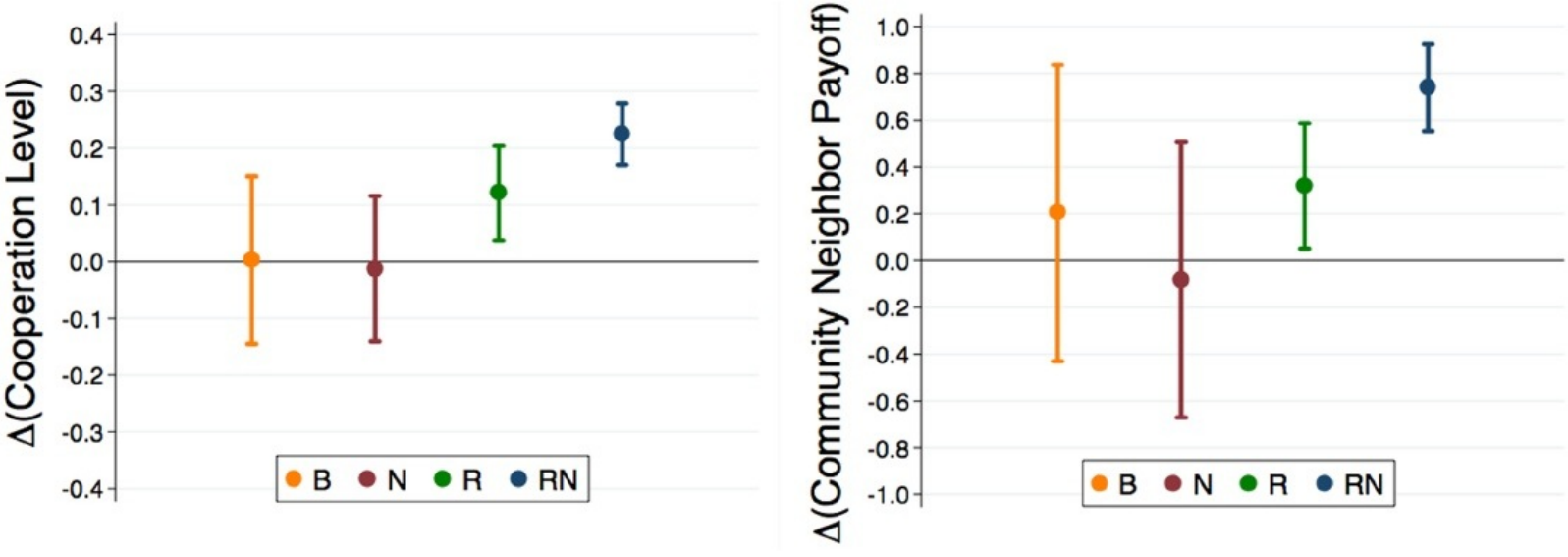
- In *RN* community *C*1 has a 37% higher level of cooperation than community *C*2
- *RN* is the only treatment where *C*1 is more cooperative than *C*2 ($p = 0.025$)





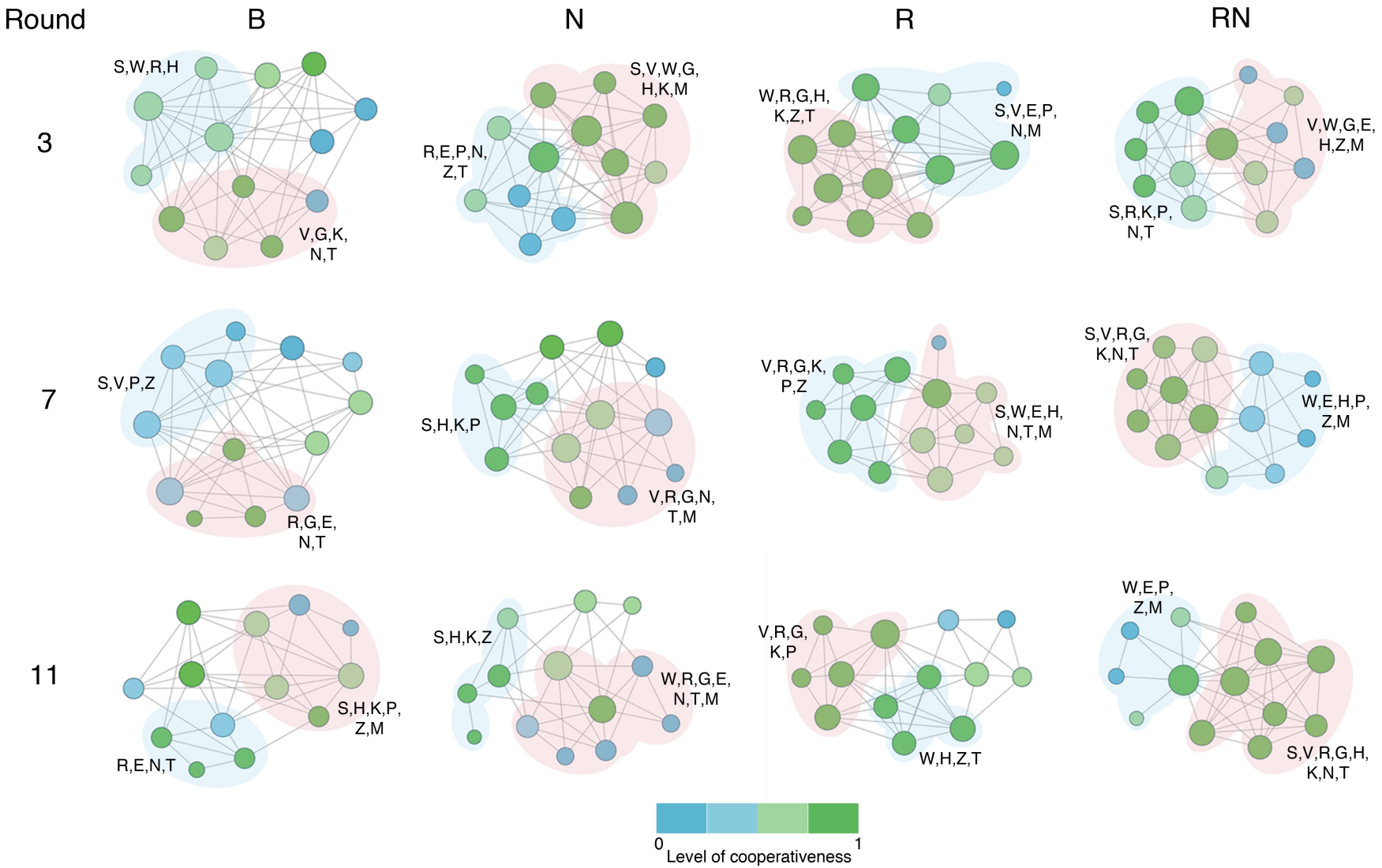
Methodology 1: A large community of cooperators

- *RN* is the only treatment where members of *C*1 generate on average more surplus from each interaction with another member of their own community compared to members of *C*2 ($p = 0.018$)

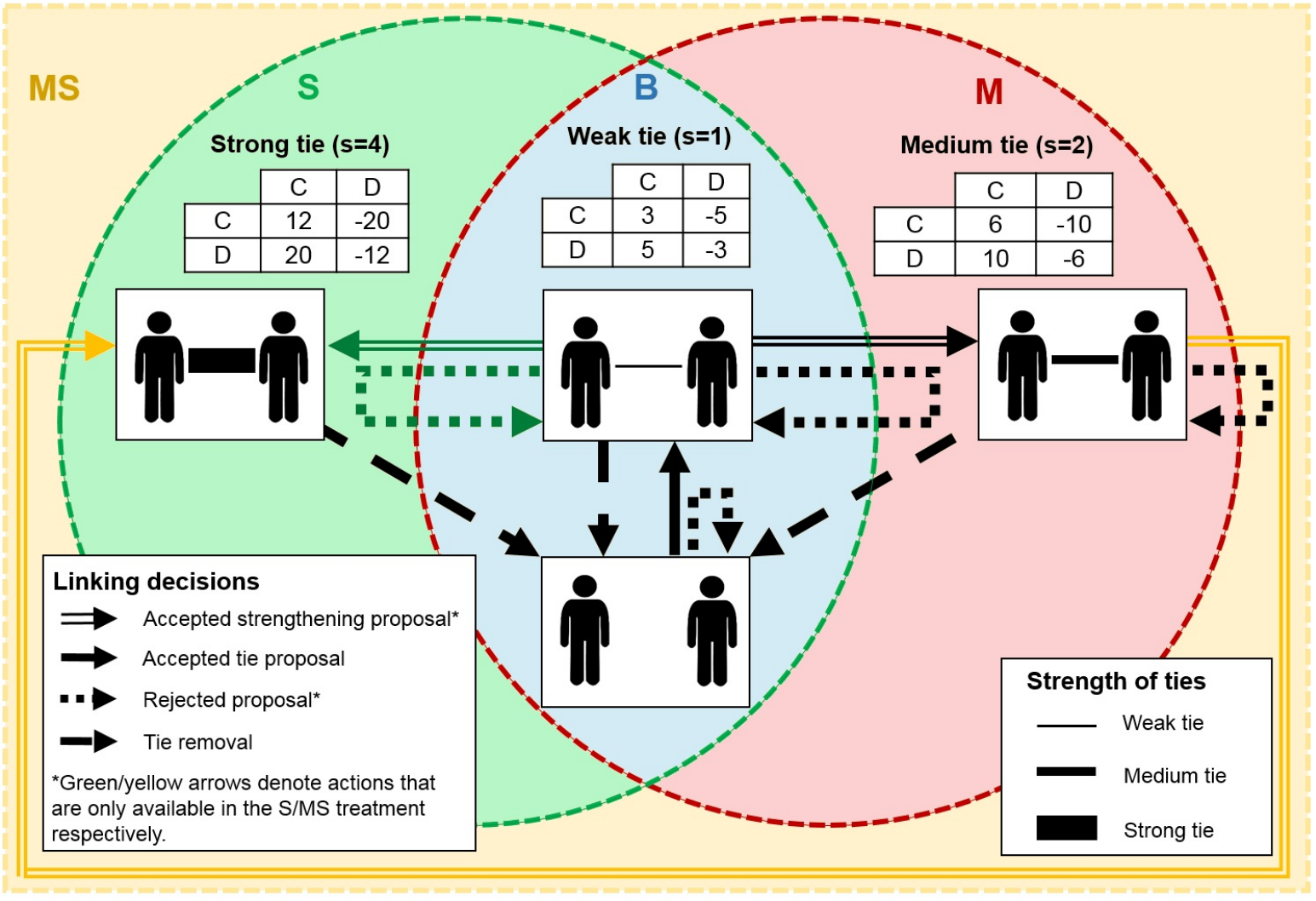


Gallo and Yan, PNAS 2015

Methodology 1: A visual summary



Recall: Study 2



Methodology 2: Composition of links

A steep change to strong links (S) makes the punishment mechanism more effective:

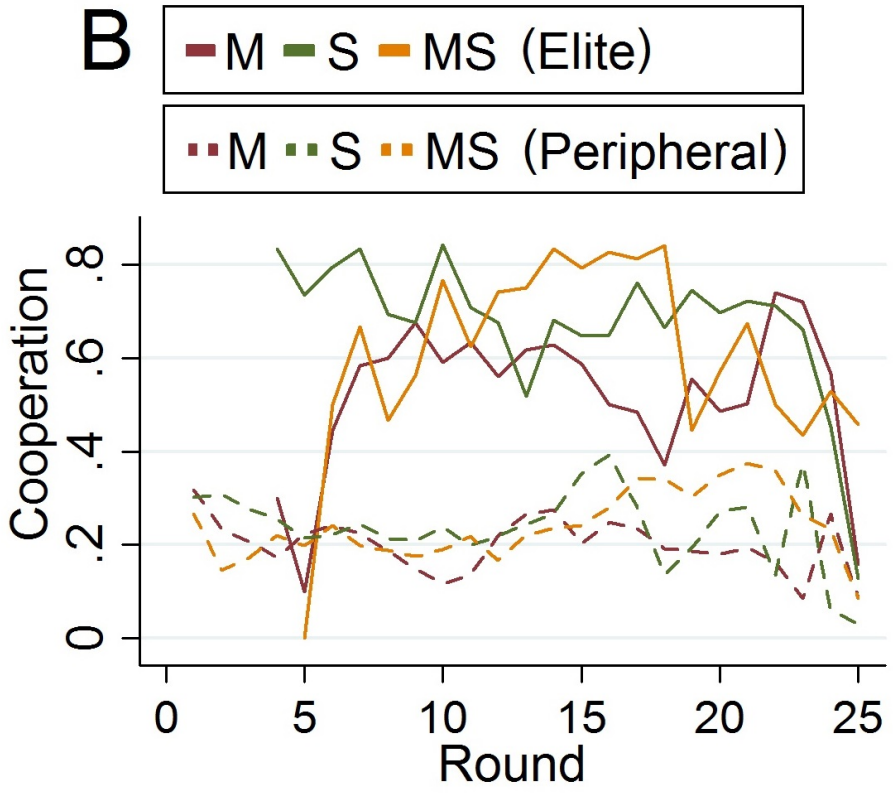
1. In treatment S participants are more selective in strengthening a tie conditional on their mutual history of actions compared to M and MS ($p = 0.03$ for both).
2. In treatment S participants are more likely to break a weak tie with a defector compared to B ($p = 0.001$), M ($p = 0.03$) and MS (LRM, $p = 0.03$).

Define two categories of participants:

- *Elite* participants have more than 80% of their ties as non-weak
- *Peripheral* participants constitute the rest of individuals.

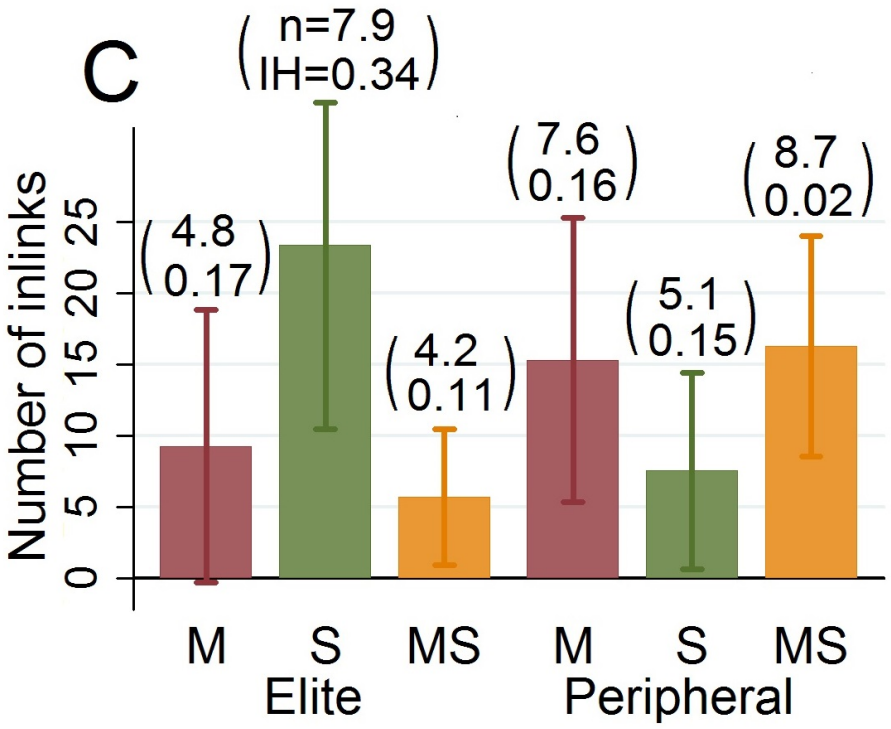
Methodology 2: Elite participants are highly cooperative

Elite individuals are significantly more cooperative than peripheral ones in *S* ($P = 0.01$), *M* ($P = 0.02$), and *MS* ($P = 0.04$).



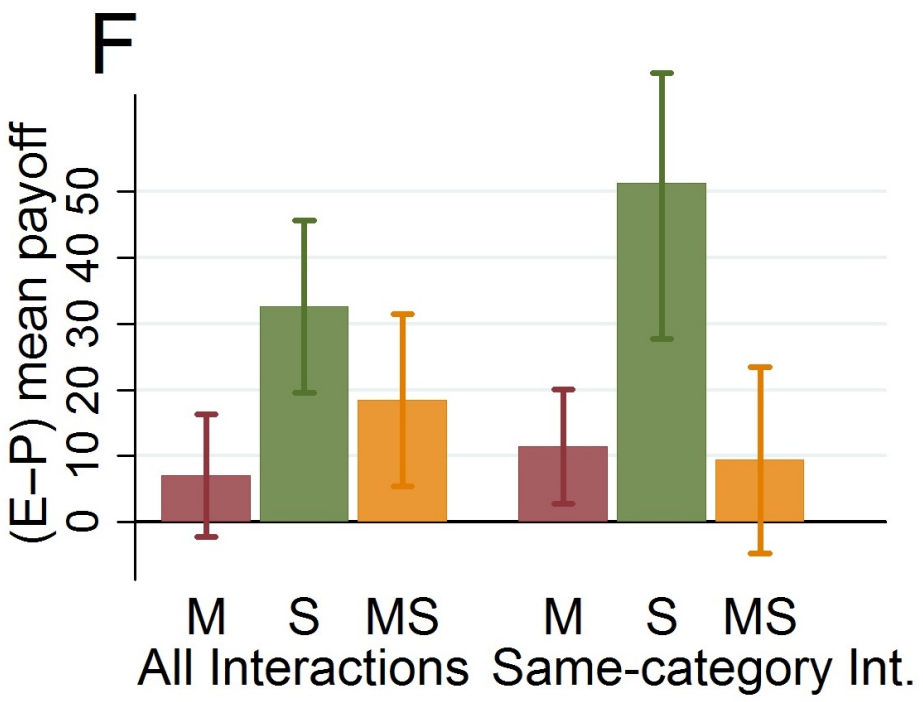
Methodology 2: Elite participants form a community in S

- There are on average 7.9 elite participants in *S*, but only 4.8 in *M* ($P = 0.008$) and 4.2 in *MS* ($P = 0.002$).
- The only category for which the *IH* index is significantly higher than 0 is elite participants in *S* ($P = 0.04$).



Methodology 2: A large community of cooperators

The difference in average payoff between elite and periphery members in *S* is significantly higher than in *M* ($P = 0.002$) and *MS* ($P = 0.03$), and there is no difference between *M* and *MS*. Differences are even more pronounced if we focus on payoffs from within category interactions.



Methodology 2: A visual summary