Supporting Information

for

Static network structure can stabilize human cooperation

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Contents

Theoretical motivation for the *b/c>k* condition

The *b/c>k* condition comes from a theory of imitation dynamics (e.g. evolutionary game theory) on networks (1). Here we sketch the intuition underlying the *b/c>k* result; we refer readers to (1) for technical details.

The theory works as follows. Each player has a strategy, either cooperate (C) or defect (D). Players sometimes change their strategy by copying a neighbor's strategy. When this happens, a neighbor is picked proportional to payoff in the previous round to be copied (i.e. if my strategy is C, and I have a D neighbor with a high payoff and a C neighbor with a low payoff, then I am more likely to switch to D; or if I am a D player with a high payoff C neighbor and low payoff D neighbor, I am more likely to switch to C). In this way, the fraction of cooperators and defectors in the population evolves over time.

It has been shown by (1) that cooperation can spread under this framework as long as *b/c>k*, which causes the network structure to generate enough clustering to make cooperators earn high payoffs. To gain an intuition for this result, consider a *k*=2 cycle with perfect assortment (Figure S1).

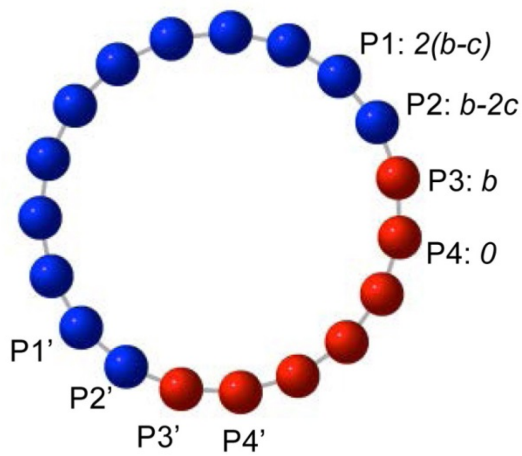


Figure S1. A k=2 cycle with perfect assortment. Blue = C, red = D. Payoffs of players P1-P4 and P1'-P4' are indicated.

Under the dynamic described above, in which players copy their neighbors, the only way the frequency of cooperation can change is if a player on the edge between clusters (i.e. players P2, P3, P2', or P3' in Figure S1) changes strategy; the reason is that, for people on the interior of a cluster, they and both neighbors are playing the same strategy and so imitation cannot lead to a change.

If P2 or P2' compare the payoffs of their neighbors, they see that the cooperator earns *2(b-c)* whereas the defector earns *b*; thus if *b/c*>2, they are more likely to copy the cooperator (and cooperation will spread on average). Similarly, if P3 or P3' compare the payoffs of their neighbors, they see that the cooperator earns *b-2c* whereas the defector earns 0; thus, again if

$b/c>2$, they are more likely to copy the cooperator. Thus for cycles, with $k=2$, $b/c>2$ is required for players to preferentially imitate cooperation (and therefore for cooperation to spread). A generalization of this logic yields the $b/c>k$ condition for cases with $k>2$ (1).

As described above, under this update rule (‘death birth updating’), a player with the same strategy as all of her neighbors cannot change strategy when updating (since whichever of her neighbors is picked will result in the strategy she is already playing). If such a change does occur, it is referred to as exploration or ‘mutation’. See below for a detailed discussion of the effect of mutation on networked cooperation.

Statistical details

Here we provide regression tables to accompany the statistics reported in the main text. Note that all regressions cluster standard errors on subject and session to account for the non-independence of repeated observations from the same subject, and from different subjects within the same session.

Experiment 1

Table S1. Cooperation in all rounds as a function of round, well-mixed indicator, and the interaction between the two. The non-significant coefficient on Round indicates no change over time in the networked condition (where Well-Mixed=0). Evaluating the net coefficient on Round for the Well-Mixed condition (i.e. coeff on Round + coeff on [Well-Mixed X Round]) gives coeff=-0.0123, p=0.053. Logistic regression clustered on subject and session.

	(1)
Well-Mixed	-0.0984
	(0.445)
Round	0.00521
	(0.00492)
Well-Mixed X Round	-0.0175*
	(0.00805)
# Players	0.207**
	(0.0762)
Constant	-0.853
	(0.805)
Observations	5,450

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Table S2. Cooperation by Well-mixed. Initially, cooperation does not vary, but later in the session there is significantly less cooperation when the population is well-mixed; this is true when considering the last half (rounds 26-50), last third (34-50) or last quarter (38-50). Logistic regression with robust standard errors clustered on subject and session.

	(1)	(2)	(3)	(4)
	Round 1	Round 26-50	Round 34-50	Round 38-50
Well-mixed	0.210	-0.849*	-0.948*	-0.891*
	(0.550)	(0.411)	(0.429)	(0.418)
# Players	0.398	0.150**	0.169**	0.172**
	(0.209)	(0.0578)	(0.0605)	(0.0632)
Constant	-2.114	-0.0946	-0.219	-0.357
	(1.735)	(0.596)	(0.615)	(0.619)
Observations	109	2,725	1,853	1,417

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

We note that these results are robust to a more conservative analysis in which we treat each session as a single data point (with value equal to the average frequency of cooperation over that session), and compare conditions using the non-parametric Wilcoxon Rank-sum test: comparing the average cooperation rates in the Networked and Well-mixed conditions shows no difference in round 1 (p=0.38), and significantly more cooperation in the Networked condition in the second half (p=0.0321), last third (p=0.0321), and last quarter (p=0.0319) of the game.

Experiment 2

Table S3. Cooperation in the later part of the game as a function of round: cooperation is stable for b/c>k but decreases in b/c≤k. Logistic regression clustered on subject and session. Models 1 and 2 are reported in the main text (second half of the game, rounds 9-15). Models 3 and 4 show that the results are robust to defining the second half the game as being rounds 8-15. Models 5 and 6 show that the results are robust to considering the last third of the game (rounds 11-15) instead of the second half.

	(1)	(2)	(3)	(4)	(5)	(6)
	Rounds 9-15		Rounds 8-15		Rounds 11-15	
	b/c>k	b/c≤k	b/c>k	b/c≤k	b/c>k	b/c≤k
Round	-0.00401	-0.0387*	-0.0218	-0.0400**	0.0109	-0.0556*
	(0.0197)	(0.0176)	(0.0145)	(0.0149)	(0.0341)	(0.0269)
# Players	0.0324	-0.00342	0.0328	-0.00472	0.0350	0.00280
	(0.0443)	(0.0278)	(0.0429)	(0.0283)	(0.0440)	(0.0279)
Constant	-0.595	0.0486	-0.373	0.0956	-0.861	0.129
	(1.121)	(0.703)	(1.057)	(0.714)	(1.156)	(0.624)
Observations	1,916	3,643	2,192	4,173	1,366	2,593

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Table S4. Cooperation in all rounds as a function of round and b/c>k indicator. Change in cooperation over round differs significantly between b/c>k and b/c≤k. Data from all rounds is included here. Model 2 demonstrates that this effect is not driven by b/c alone. Logistic regression clustered on subject and session.

	(1)	(2)
b/c>k	0.249	0.0287
	(0.200)	(0.214)
Round	-0.0700***	-0.0905***
	(0.00803)	(0.0186)
b/c>k X Round	0.0368**	0.0269**
	(0.0115)	(0.00941)
# Players	0.00312	0.00953
	(0.0224)	(0.0205)
b/c		0.105
		(0.0584)
b/c X Round		0.00572
		(0.00374)
Constant	0.243	-0.251
	(0.537)	(0.561)
Observations	12,093	12,093

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Table S5. Cooperation in round 1 and round 15 by b/c>k. Initially, cooperation does not vary, but at the end of the game, there is significantly more cooperation when b/c>k. Logistic regression with robust standard errors clustered on subject and session.

	(1) Round 1	(2) Round 1	(3) Round 15	(4) Round 15
b/c > k	0.176	-0.00168	0.701**	0.446*
	(0.203)	(0.222)	(0.230)	(0.225)
# Players	0.00754	0.0112	0.0316	0.0372
	(0.0264)	(0.0247)	(0.0269)	(0.0267)
b/c		0.0871		0.130*
		(0.0502)		(0.0623)
Constant	0.280	-0.0932	-1.328*	-1.902**
	(0.609)	(0.545)	(0.657)	(0.709)
Observations	840	840	787	787

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

We note that similar results are obtained using only one observation per session with Wilcoxon Rank-sums. We find significantly more cooperation in Round 15 when $b/c>k$ than $b/c\leq k$ (Rank-sum, p=0.004), $b/c=k$ (Rank-sum, p=0.006) or $b/c<k$ (Rank-sum, p=0.033); and no significant difference between $b/c=k$ and $b/c<k$ (p=0.45).

Table S6. Level of assortment by b/c>k. Assortment is defined as a cooperator's average number of cooperative neighbors minus a defector's average number of neighbors. As assortment is a session-level characteristic rather than an individual level characteristic, we have 1 observation per session per round. The constant in Model 1 indicates the estimate for assortment when b/c≤k (not significantly different from zero). To estimate the level of assortment when b/c>k, we evaluate the net coefficient (b/c>k coefficient + constant = 0.142, p=0.0005; significantly greater than 0). Linear regression with robust standard errors clustered on session.

	(1)	(2)	(3)
b/c>k	0.151***	0.135**	0.142**
	(0.0390)	(0.0400)	(0.0414)
b/c			-0.00222
			(0.0115)
k		-0.00776	-0.00665
		(0.00898)	(0.0118)
Constant	-0.00933	0.0269	0.0291
	(0.0125)	(0.0464)	(0.0455)
Observations	539	539	539
R-squared	0.156	0.159	0.159

Robust standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Table S7. Round payoff relative to session average by decision (cooperate or defect) and b/c>k. The dependent variable is the subject's payoff in the current round minus the average payoff of all subjects in that session. To make payoffs comparable across values of b/c and k, we normalize payoffs, dividing by the largest possible relative payoff (a player who receives cooperation from all of her neighbors, earning a payoff bk, relative to the average of a group containing her and N-1 other players all receiving the lowest possible payoff of –ck). We also show that results are qualitatively equivalent without the normalization in models 3 and 4. To evaluate the effect on relative payoff of cooperating when b/c≤k, we examine the Cooperate coefficient in Model 1 (significantly less than 0). To evaluate the effect on relative payoff of cooperation when b/c>k, we test the net coefficient (Cooperate coefficient + b/c>k X Cooperate coefficient = -0.041, p=0.152; not significantly different from 0). Linear regression with robust standard errors clustered on subject and session.

	(1)	(2)	(3)	(4)
	Normalized	Normalized	Not Normalized	Not Normalized
b/c>k	-0.0817***	-0.0598***	-14.92***	-24.44***
	(0.0175)	(0.0159)	(3.228)	(3.938)
Cooperate	-0.238***	-0.370***	-42.78***	-24.70**
	(0.0161)	(0.0242)	(3.823)	(7.492)
b/c>k X Cooperate	0.197***	0.126***	35.85***	47.49***
	(0.0326)	(0.0279)	(5.675)	(6.872)
b/c		-0.0100*		4.368***
		(0.00390)		(1.048)
b/c X Cooperate		0.0384***		-5.595**
		(0.00688)		(2.157)
Constant	0.105***	0.137***	18.91***	5.176
	(0.00659)	(0.0147)	(2.127)	(3.385)
Observations	12,093	12,093	12,093	12,093
R-squared	0.176	0.190	0.162	0.172

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Table S8. Cooperation in the second half of the game (rounds 9-15) as a function of round, comparing network structured versus well-mixed population, all for b/c>k. Logistic regression clustered on subject and session.

	(1) Structured	(2) Well-mixed
Round	-0.00401	-0.0623**
	(0.0197)	(0.0219)
# Players	0.0324	0.0954*
	(0.0443)	(0.0396)
Constant	-0.595	-1.926
	(1.121)	(1.169)
Observations	1,916	2,216

Standard errors in parentheses
*** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table S9. Cooperation in all rounds as a function of round and well-mixed indicator. Includes data from all rounds. Logistic regression clustered on subject and session.

	(1)
Round	-0.0332***
	(0.00851)
# Players	0.0710***
	(0.0217)
Well-mixed	-0.0726
	(0.224)
Well-mixed X Round	-0.0303**
	(0.0120)
Constant	-1.170**
	(0.544)
Observations	8,944

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table S10. Cooperation in round 1 and round 15 by well-mixed. Initially, cooperation does not vary, but at the end of the game, there is significantly less cooperation when the population is well-mixed. Logistic regression with robust standard errors clustered on subject and session.

	(1)	(2)
	Round 1	Round 15
Well-mixed	-0.168	-0.468*
	(0.198)	(0.220)
# Players	0.0967***	0.0463
	(0.0215)	(0.0285)
Constant	-1.721**	-0.987
	(0.540)	(0.771)
Observations	613	586

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Table S11. Level of assortment by well-mixed. The constant indicates the estimate for assortment in the network structured population (significantly greater than zero). To estimate the level of assortment when the population is well-mixed, we evaluate the net coefficient (Well-mixed coefficient + Constant = -0.055, p=0.203; not significantly different from 0). Linear regression with robust standard errors clustered on session.

	(1)
Well-mixed	-0.155***
	(0.0387)
Constant	0.141***
	(0.0372)
Observations	360
R-squared	0.143

Robust standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Table S12. Round payoff relative to session average by decision (cooperate or defect) and well-mixed. To evaluate the effect on relative payoff of cooperating in the network structured population, we examine the Cooperate coefficient in Model 1 (not significantly different from 0). To evaluate the effect on relative payoff of cooperation in the well-mixed population, we test the net coefficient (Cooperate coefficient + Well-mixed X Cooperate coefficient = -0.162, p<0.0001). Linear regression with robust standard errors clustered on subject and session.

	(1) Normalized	(2) Not Normalized
Well-Mixed	0.0649***	9.533**
	(0.0181)	(3.070)
Cooperate	-0.0407	-6.924
	(0.0286)	(4.225)
Well-Mixed X Cooperate	-0.121***	-17.88***
	(0.0319)	(5.045)
Constant	0.0234	3.983
	(0.0163)	(2.446)
Observations	8,944	8,944
R-squared	0.051	0.047

Standard errors in parentheses
*** p<0.001, ** p<0.01, * p<0.05

Conditions for the evolution of cooperation on networks with mutation

As described in the main text, in our *b/c>k* conditions, we observe that defectors with all defecting neighbors switched to cooperation 17.4% of the time (D-to-C mutation), and cooperators with all cooperating neighbors switched to defection 5.1% of the time (C-to-D mutation). D-to-C mutations are beneficial for cooperation, as they increase the overall level of cooperation and also have the possibility of creating new clusters of cooperators. It is C-to-D mutations that are potentially harmful for cooperation, as that disrupt cooperative clusters.

Here, we ask what predictions theory makes about the evolution of cooperation in the presence of these levels of mutation, based on the work of (2). Asymmetric mutation rates have not been studied theoretically. Therefore, we make the conservative assumption of a symmetric 5.1% chance of spontaneously changing strategy (neglecting the increased likelihood of defectors switching to cooperators, and biasing our estimate *against* cooperation).

For a cycle with k=2, theory predicts that cooperation will be favored when

$$\frac{b}{c} > \frac{2(1-u)}{1-\sqrt{u(2-u)}}$$

where u is the probability of mutating (defined here as choosing C or D with 50% chance – thus a 5.1% chance of changing strategy in our data is equivalent to u=0.102). Substituting u=0.102 yields a condition of *b/c*>3.35 for cooperation to be favored on a cycle with k=2, a criterion which is satisfied in both of our k=2 conditions where *b/c>k* ([b/c=4, k=2] and [b/c=6, k=2]).

Analytical results have not been previous derived for cycles with k>2, but a cycle with k=4 may be well approximated by a Cayley graph of the same degree. Theory predicts that cooperation will be favored on a Cayley graph with degree k when

$$\frac{b}{c} > \frac{2k(1-u)(k-1)}{(k-1)(k-\sqrt{k^2-4(k-1)(1-u)^2})}$$

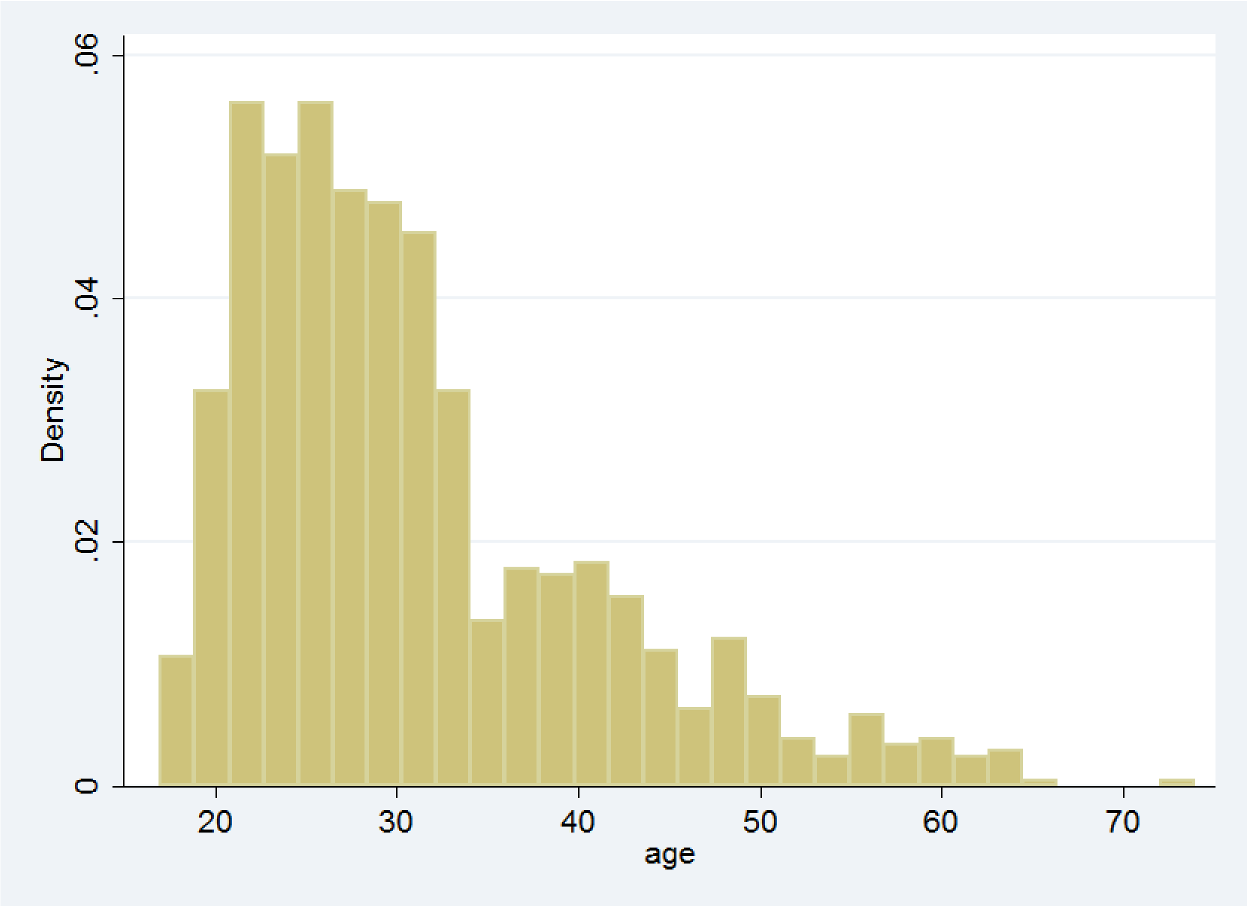
Substituting k=4 and u=0.102 yields a condition of *b/c*>4.99, which again is satisfied by our k=4 condition where *b/c>k* (*b/c*=6, k=4). Thus, the success of cooperation in our *b/c>k* experimental conditions comports well with theoretical predictions, even taking into account exploration/mutation.

Experiment 2 Participant Demographics

Because the MTurk population is much more diverse than typical undergraduate laboratory populations, we provide background demographics on our MTurk subjects.

Gender: 48.5% female.

Age: Mean 31.1 years old.



Education:

Less than a high school degree	1.0%
Vocational training	3.7%
High school diploma	16.6%
Attended college	28.0%
Bachelor's degree	36.7%
Graduate degree	13.9%
Unknown	0.1%

Annual income:

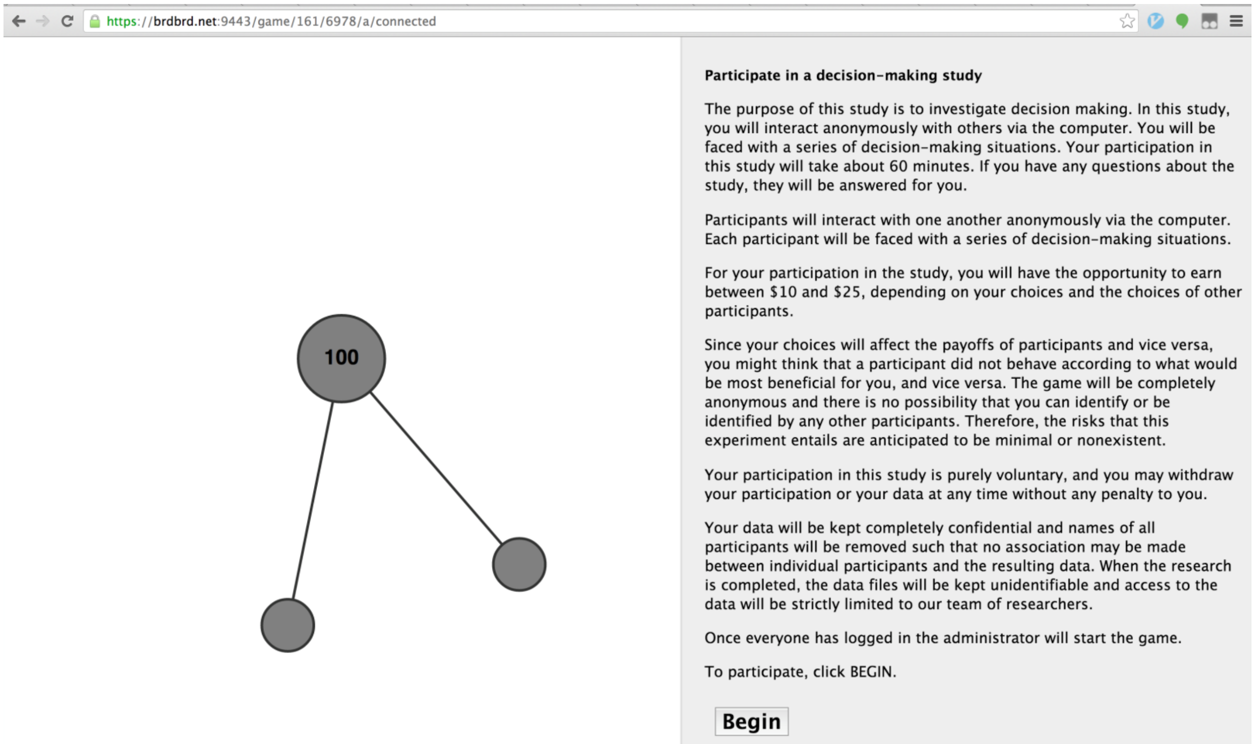
$5,000 or less	17.7%
$5,001 to $10,000	10.4%
$10,001 to $15,000	9.4%
$15,001 - $25,000	13.1%
$25,001 - $35,000	13.9%
$35,001 - $50,000	14.8%
$50,001 - $65,000	9.0%
$65,001 - $80,000	5.2%
$80,001 - $100,000	3.8%
Over $100,000	2.8%

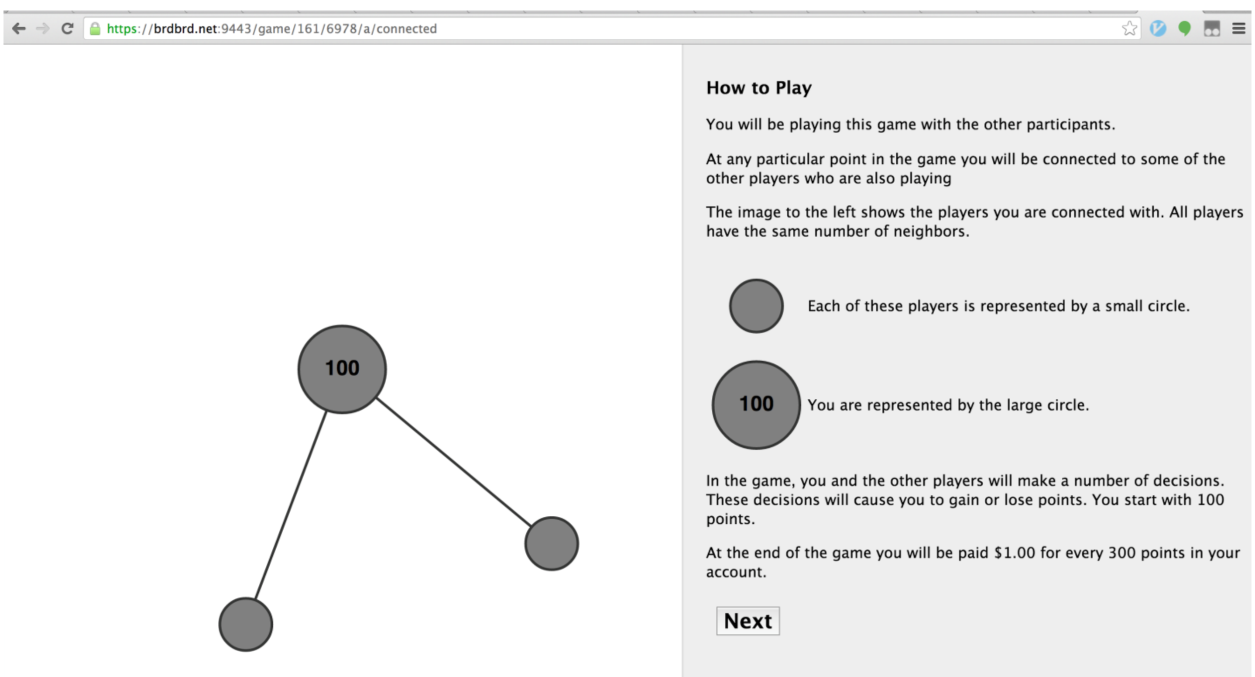
Country of residence:

United States	81.3%
India	11.9%
Canada	1.4%
Romania	0.9%
United Kingdom	0.6%
Macedonia	0.6%
Serbia	0.6%
Croatia	0.3%
Poland	0.3%
Germany	0.2%
Hungary	0.2%
Latvia	0.2%
Mexico	0.2%
Spain	0.2%
Afghanistan	0.1%
Belgium	0.1%
Bosnia and Herzegovina	0.1%
Brazil	0.1%
Dominica	0.1%
Grenada	0.1%
Ireland	0.1%
Italy	0.1%
Jamaica	0.1%
Qatar	0.1%
Russian Federation	0.1%
Singapore	0.1%
Switzerland	0.1%
Taiwan	0.1%
Turkey	0.1%

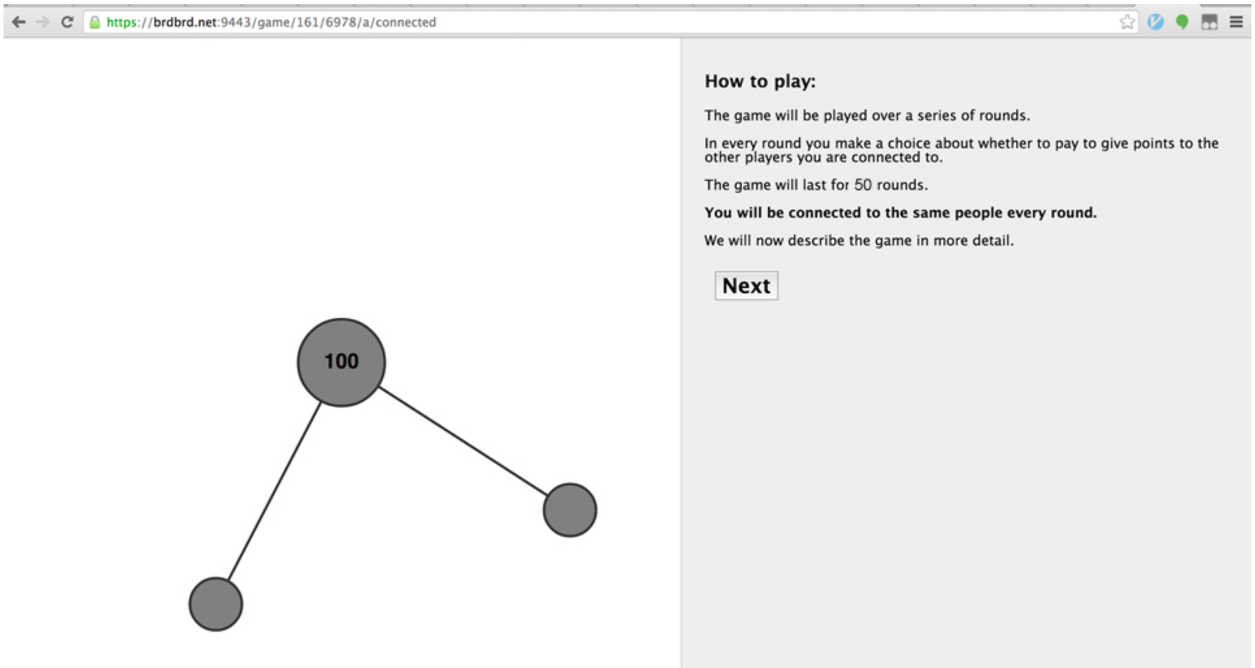
Instructions & screenshots

Experiment 1

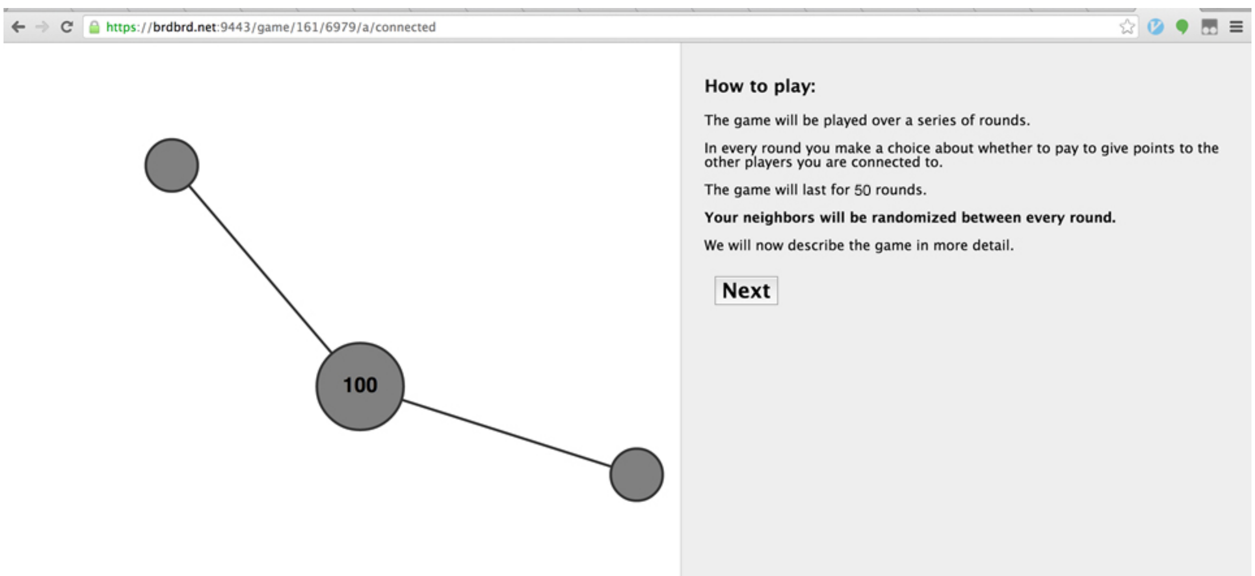


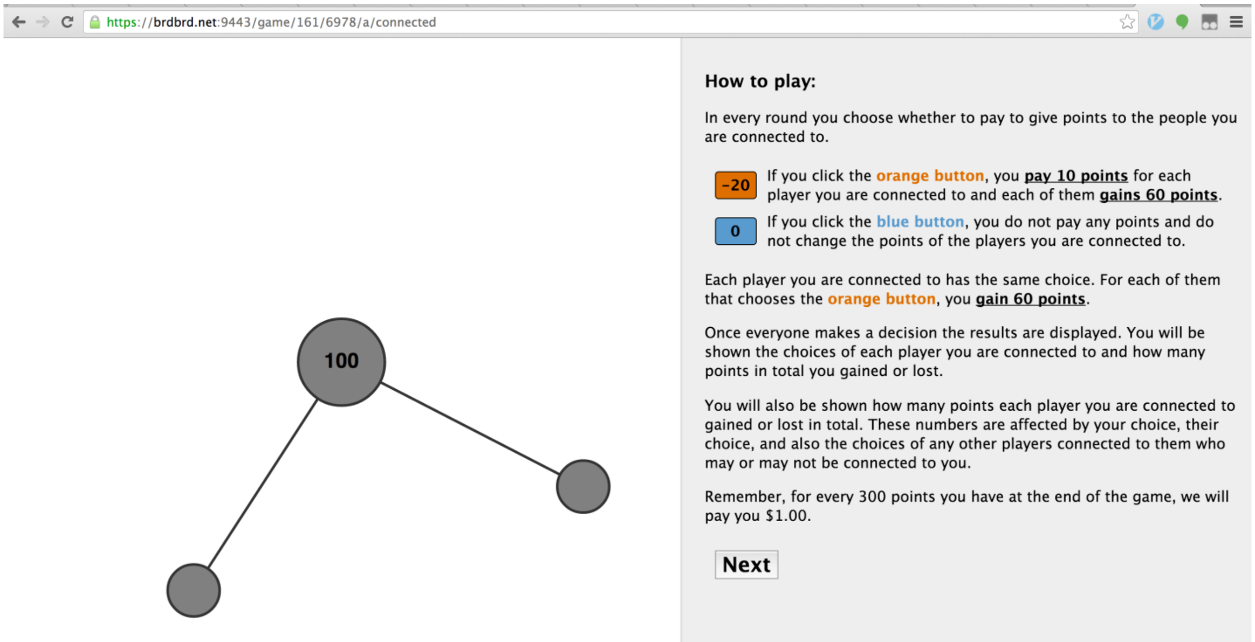


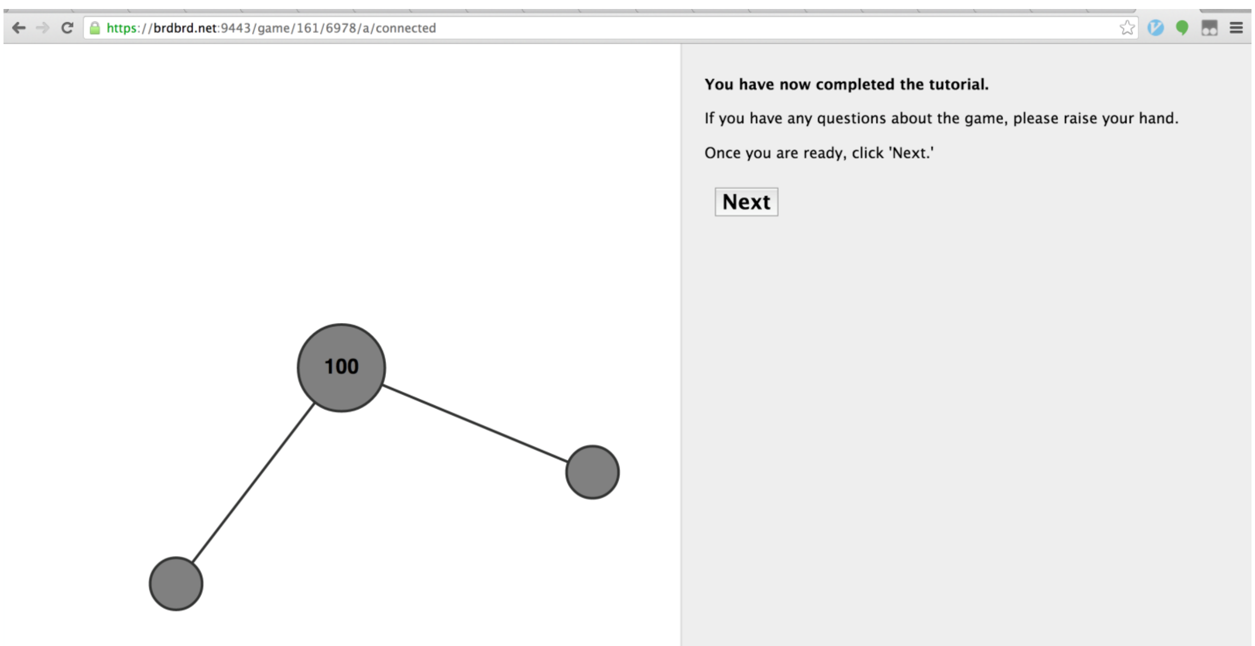
Networked condition:

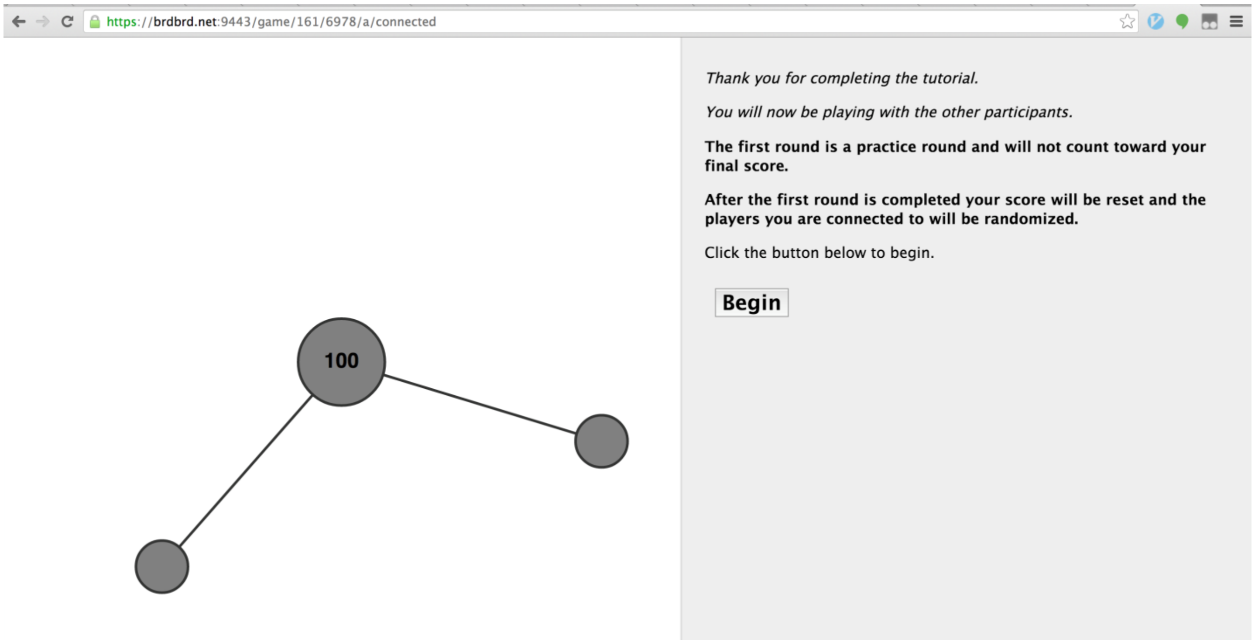


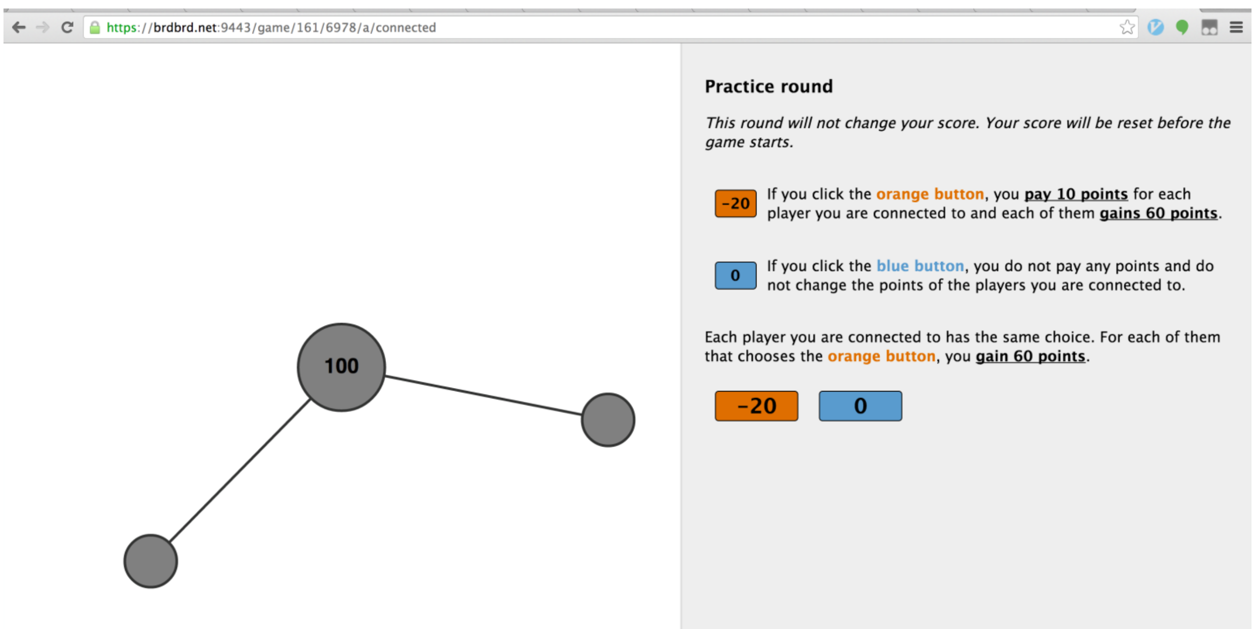
Well-mixed condition:

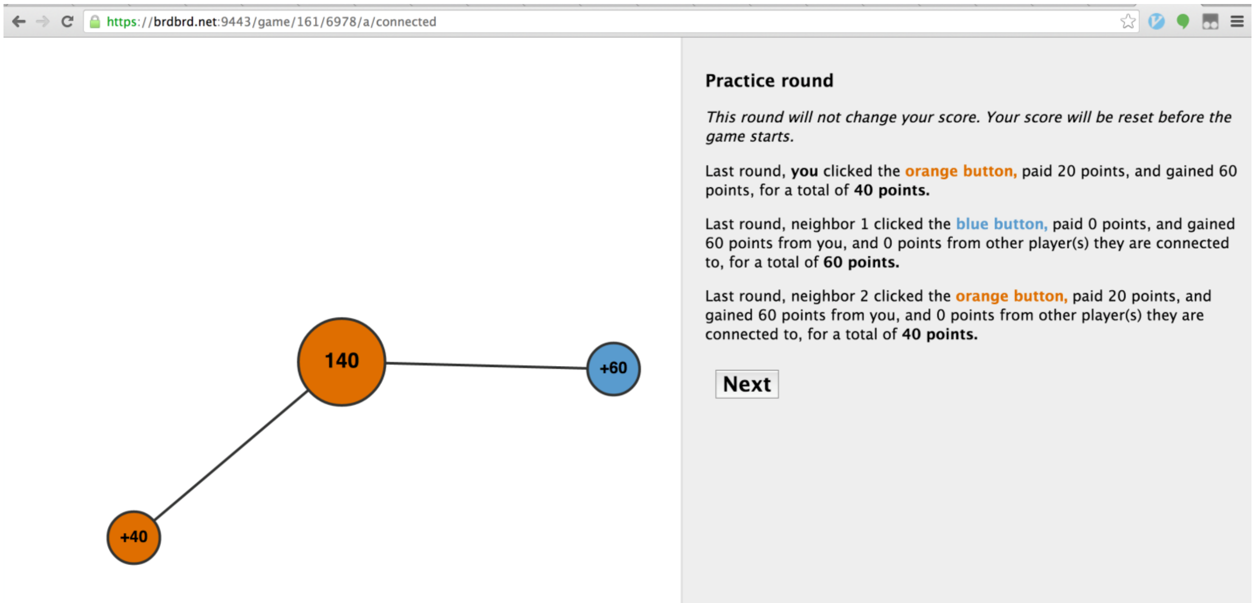


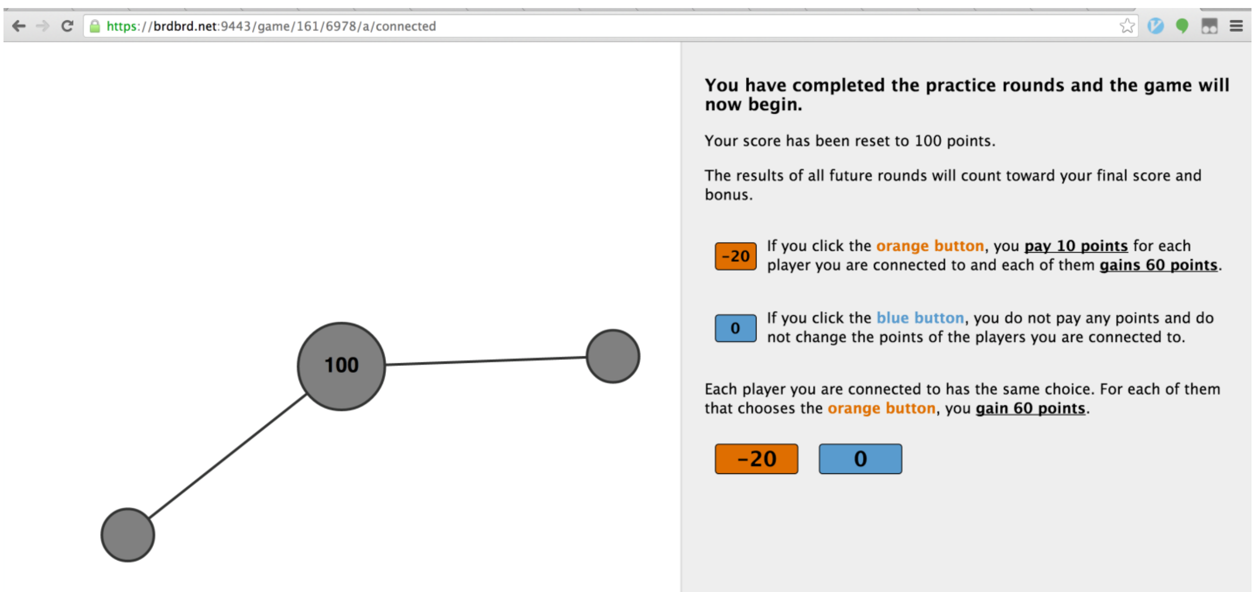

https://brdbrd.net:9443/game/161/6978/a/connected
100
How to play:
In every round you choose whether to pay to give points to the people you are connected to.
-20
If you click the orange button, you pay 10 points for each player you are connected to and each of them gains 60 points.
0
If you click the blue button, you do not pay any points and do not change the points of the players you are connected to.
Each player you are connected to has the same choice. For each of them that chooses the orange button, you gain 60 points.
Once everyone makes a decision the results are displayed. You will be shown the choices of each player you are connected to and how many points in total you gained or lost.
You will also be shown how many points each player you are connected to gained or lost in total. These numbers are affected by your choice, their choice, and also the choices of any other players connected to them who may or may not be connected to you.
Remember, for every 300 points you have at the end of the game, we will pay you $1.00.
Next

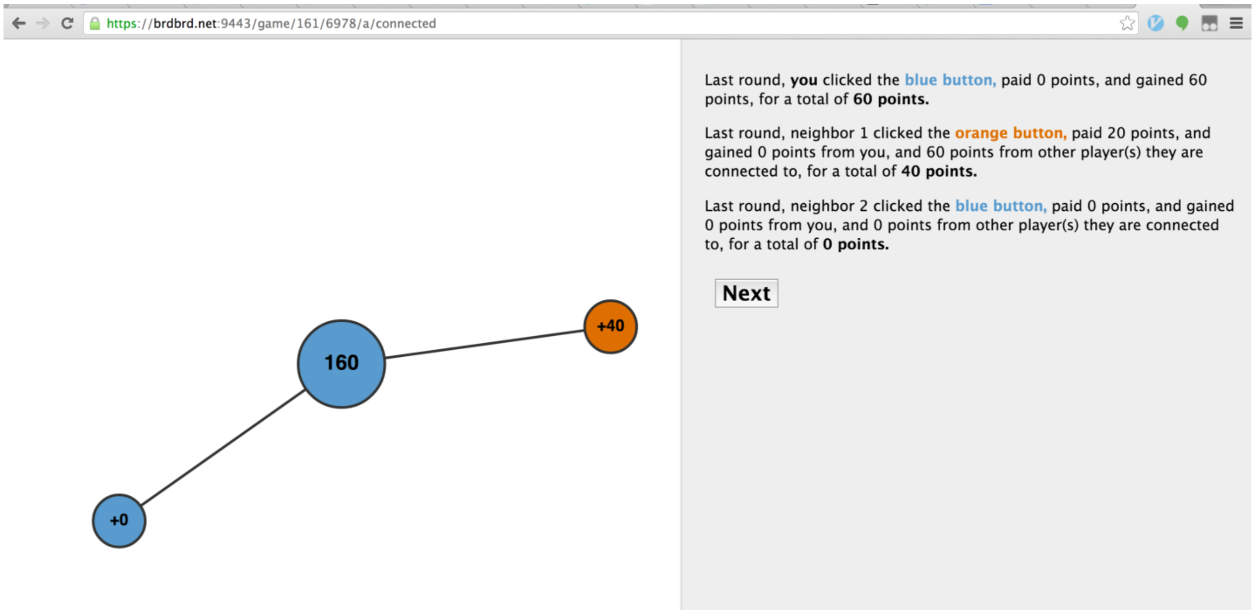

https://brdbrd.net:9443/game/161/6978/a/connected
100
You have now completed the tutorial.
If you have any questions about the game, please raise your hand.
Once you are ready, click 'Next.'
Next

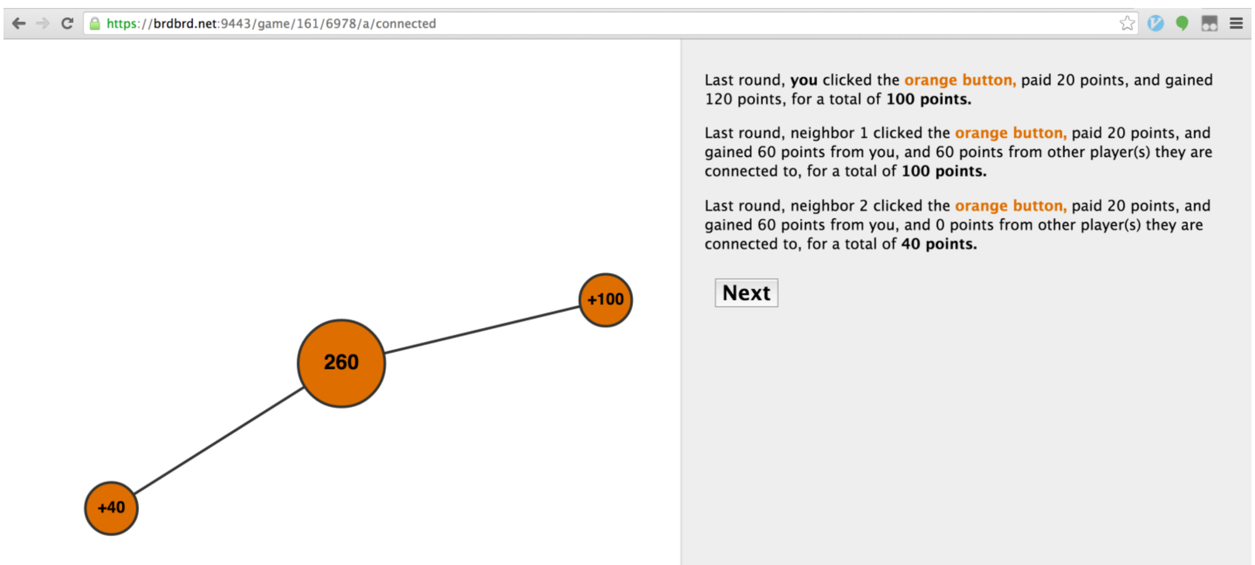

https://brdbrd.net:9443/game/161/6978/a/connected
100
Thank you for completing the tutorial.
You will now be playing with the other participants.
The first round is a practice round and will not count toward your final score.
After the first round is completed your score will be reset and the players you are connected to will be randomized.
Click the button below to begin.
Begin


https://brdbrd.net:9443/game/161/6978/a/connected
100
Practice round
This round will not change your score. Your score will be reset before the game starts.
-20
If you click the orange button, you pay 10 points for each player you are connected to and each of them gains 60 points.
0
If you click the blue button, you do not pay any points and do not change the points of the players you are connected to.
Each player you are connected to has the same choice. For each of them that chooses the orange button, you gain 60 points.
-20
0


https://brdbrd.net:9443/game/161/6978/a/connected
140
+60
+40
Practice round
This round will not change your score. Your score will be reset before the game starts.
Last round, you clicked the orange button, paid 20 points, and gained 60 points, for a total of 40 points.
Last round, neighbor 1 clicked the blue button, paid 0 points, and gained 60 points from you, and 0 points from other player(s) they are connected to, for a total of 60 points.
Last round, neighbor 2 clicked the orange button, paid 20 points, and gained 60 points from you, and 0 points from other player(s) they are connected to, for a total of 40 points.
Next

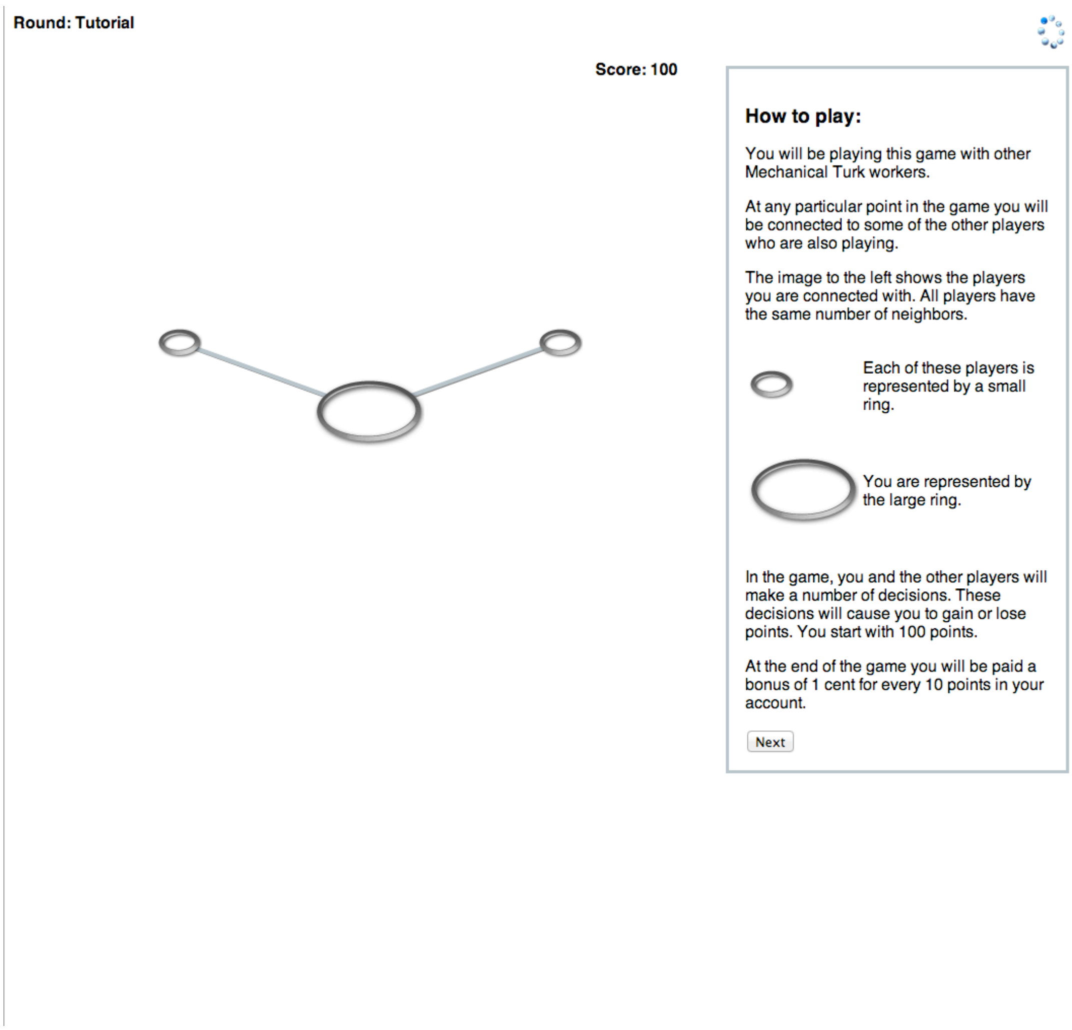

https://brdbrd.net:9443/game/161/6978/a/connected
100
You have completed the practice rounds and the game will now begin.
Your score has been reset to 100 points.
The results of all future rounds will count toward your final score and bonus.
-20
If you click the orange button, you pay 10 points for each player you are connected to and each of them gains 60 points.
0
If you click the blue button, you do not pay any points and do not change the points of the players you are connected to.
Each player you are connected to has the same choice. For each of them that chooses the orange button, you gain 60 points.
-20
0

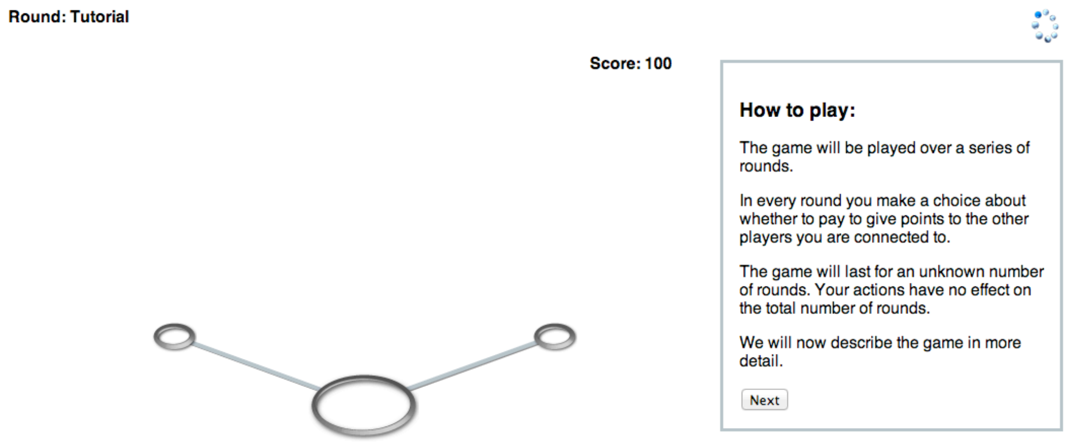

https://brdbrd.net:9443/game/161/6978/a/connected
Last round, you clicked the blue button, paid 0 points, and gained 60 points, for a total of 60 points.
Last round, neighbor 1 clicked the orange button, paid 20 points, and gained 0 points from you, and 60 points from other player(s) they are connected to, for a total of 40 points.
Last round, neighbor 2 clicked the blue button, paid 0 points, and gained 0 points from you, and 0 points from other player(s) they are connected to, for a total of 0 points.
Next
160
+40
+0


https://brdbrd.net:9443/game/161/6978/a/connected
Last round, you clicked the orange button, paid 20 points, and gained 120 points, for a total of 100 points.
Last round, neighbor 1 clicked the orange button, paid 20 points, and gained 60 points from you, and 60 points from other player(s) they are connected to, for a total of 100 points.
Last round, neighbor 2 clicked the orange button, paid 20 points, and gained 60 points from you, and 0 points from other player(s) they are connected to, for a total of 40 points.
Next
260
+100
+40

Experiment 2

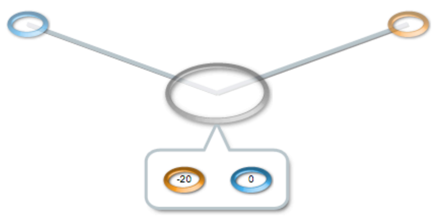
Here we show sample instructions and play screenshots for Experiment 2, from the networked b/c=6, k=2 game




Round: Tutorial
Score: 100
How to play:
The game will be played over a series of rounds.
In every round you make a choice about whether to pay to give points to the other players you are connected to.
The game will last for an unknown number of rounds. Your actions have no effect on the total number of rounds.
We will now describe the game in more detail.
Next

Round: Tutorial

Score: 100



How to play:

In every round you choose whether to pay to give points to the people you are connected to.

If you click the **orange ring**, you **pay 10 points** for each player you are connected to and each of them **gains 60 points**.

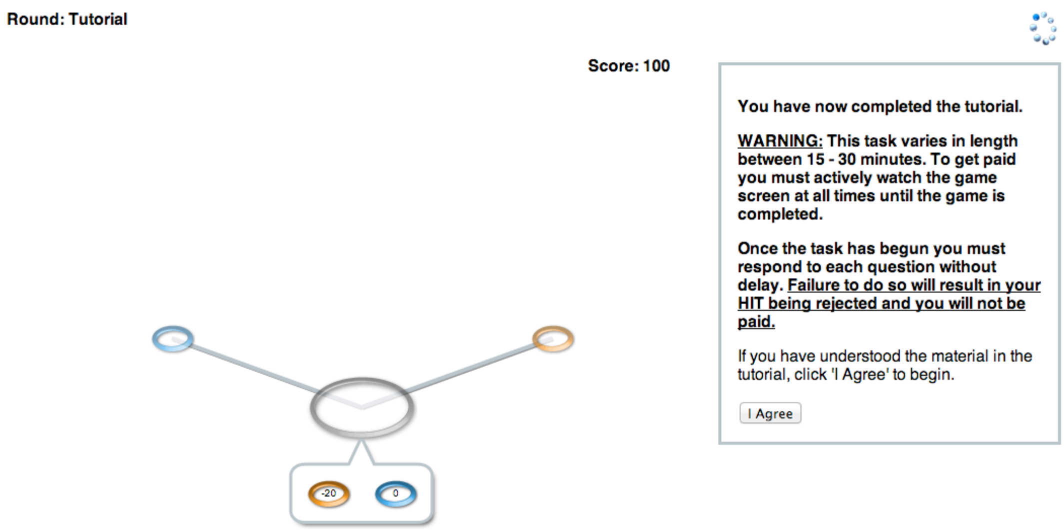
If you click the **blue ring**, you do not pay any points and do not change the points of the players you are connected to.

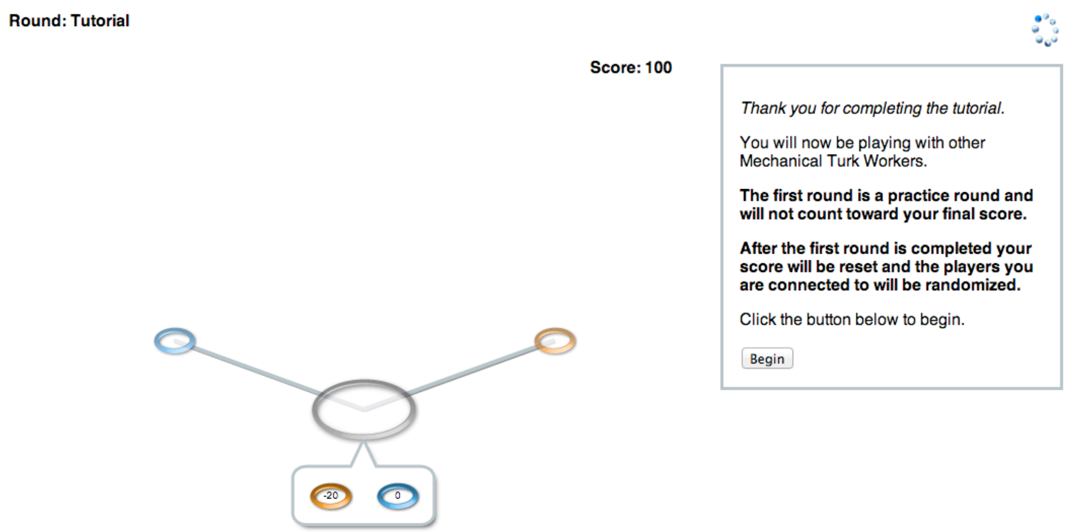
Each player you are connected to has the same choice. For each of them that chooses the **orange ring**, you **gain 60 points**.

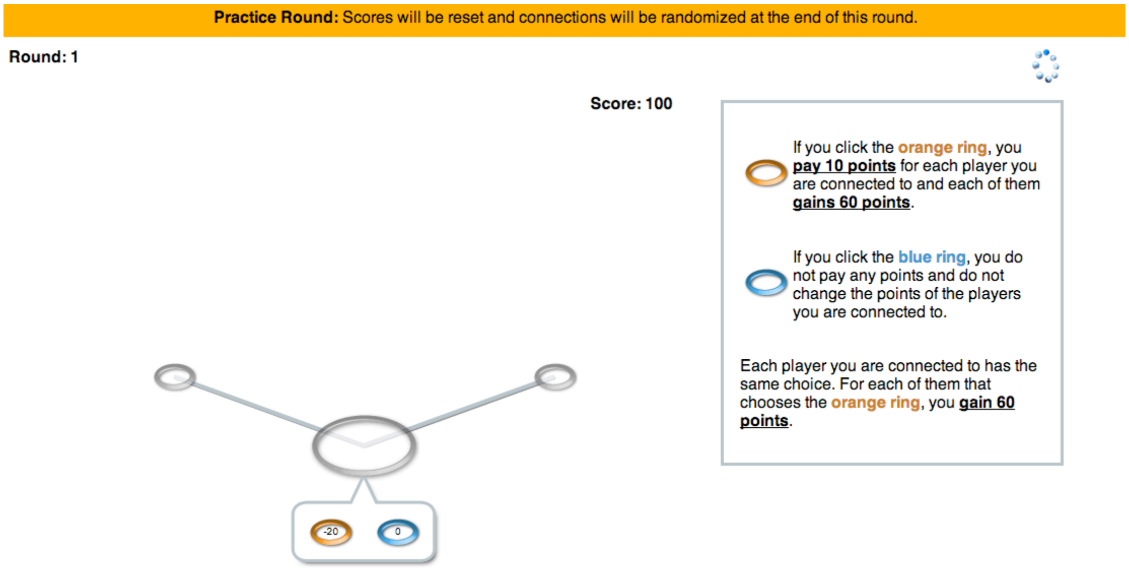
Once everyone makes a decision the results are displayed. You will be shown the choices of each player you are connected to and how many points in total you gained or lost.

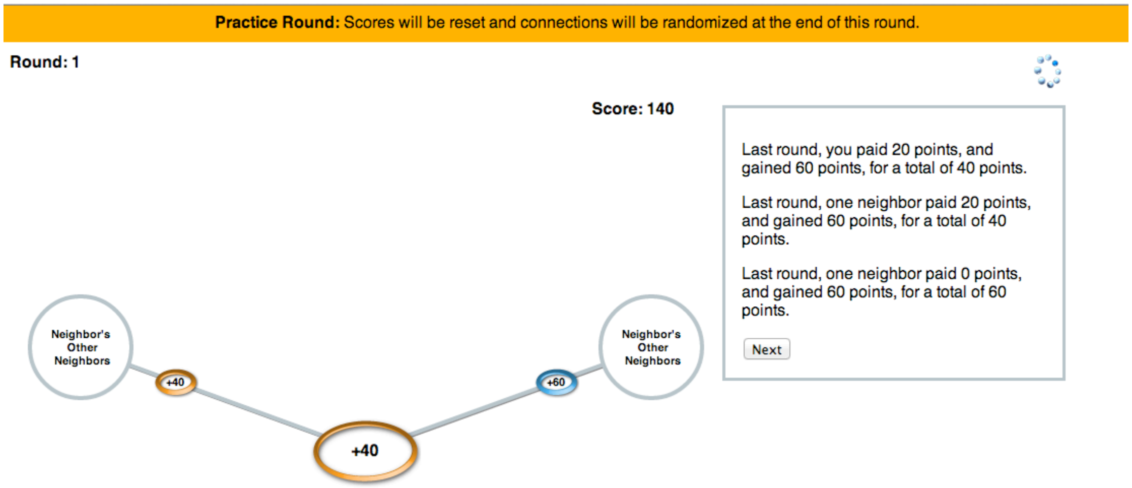
Remember, for every 10 points you have at the end of the game, we will add 1 cent to your bonus.

Next


Round: Tutorial
Score: 100
-20
0
You have now completed the tutorial.
WARNING: This task varies in length between 15 - 30 minutes. To get paid you must actively watch the game screen at all times until the game is completed.
Once the task has begun you must respond to each question without delay. Failure to do so will result in your HIT being rejected and you will not be paid.
If you have understood the material in the tutorial, click 'I Agree' to begin.
I Agree


Round: Tutorial
Score: 100
-20
0
Thank you for completing the tutorial.
You will now be playing with other Mechanical Turk Workers.
The first round is a practice round and will not count toward your final score.
After the first round is completed your score will be reset and the players you are connected to will be randomized.
Click the button below to begin.
Begin


Practice Round: Scores will be reset and connections will be randomized at the end of this round.
Round: 1
Score: 100
-20
0
If you click the orange ring, you pay 10 points for each player you are connected to and each of them gains 60 points.
If you click the blue ring, you do not pay any points and do not change the points of the players you are connected to.
Each player you are connected to has the same choice. For each of them that chooses the orange ring, you gain 60 points.



The last two screens then repeated for 15 rounds, without the orange 'practice round' header. Note that in this screen, the total payoff for the round of each neighbor is shown, along with the player's own total payoff for the round.

References

1. Ohtsuki H, Hauert C, Lieberman E, & Nowak MA (2006) A simple rule for the evolution of cooperation on graphs and social networks. *Nature* 441(7092):502-505.
2. Allen B, Traulsen A, Tarnita CE, & Nowak MA (2011) How mutation affects evolutionary games on graphs. *Journal of theoretical biology* 299:97-105.