Neuron

Supplemental Information

A Neurocomputational Model of Altruistic Choice and Its Implications

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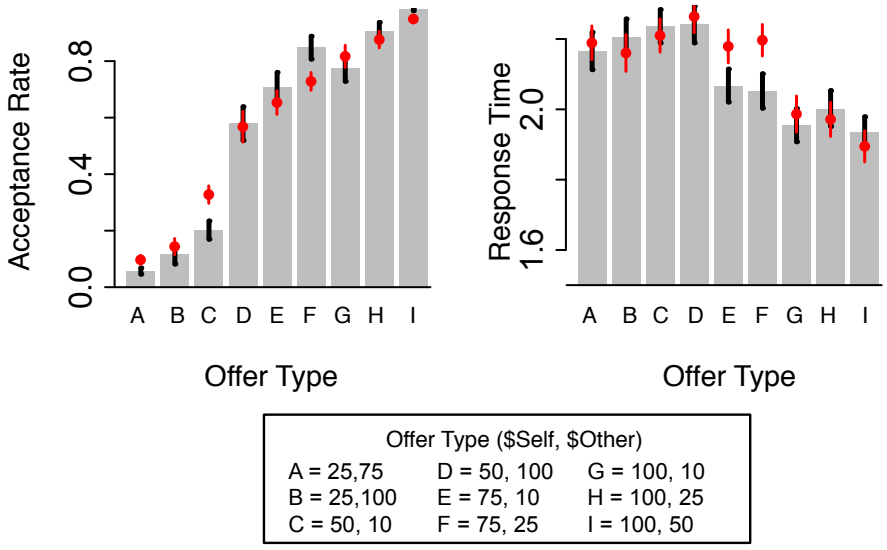
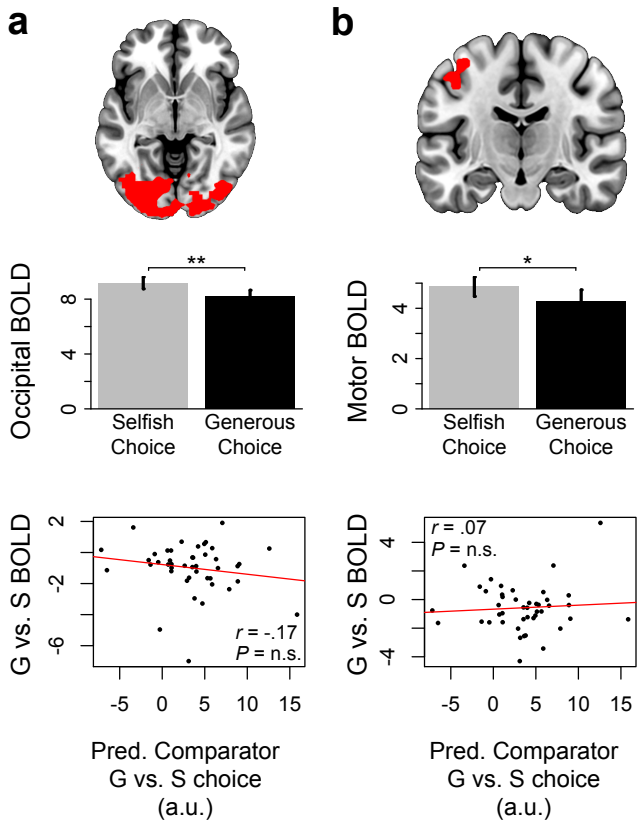


Supplementary Figure S1, Related to Figure 2. Model fits to behavior, allowing parameters to vary by whether $Self > $Other. Within-subject observed behavior (grey bars) and predicted behavior (red circles) of acceptance likelihood (right) and average response time (left) for each of the 9 proposal-types.



Supplementary Figure S2, Related to Figure 5. Poor fit to model predictions for BOLD responses during generous (G) vs. selfish (S) choices in value-modulated regions that are unlikely to be involved in the integration and comparison process. Top: occipital (A) and motor (B) regions correlate with value at the time of choice (P < .0001, uncorrected, masks shown in red). Middle: In contrast to vmPFC and TPJ, both regions show *lower* response on trials when a subject chose generously. Bottom: In neither region do individual differences in the response to G vs. S choices correlate with model-predicted comparator differences. *P=.02; **P=.0002.

Supplementary Table S1. Parameter values estimated separately in the realm of advantageous and disadvantageous inequality, Related to Table 1. w_{Self} and w_{Other} represent weights applied to the relative value of *$Self* and *$Other* on each trial compared to the default. *NDT*: non-decision time. *b* and *d*: starting value and collapse rate of the decision threshold.

Parameter	$S > $O	$S < $O	T-statistic	P-value	R	P-value
w_{Self}	.006±.002	.009±.004	5.34	< .001	.16	.25
w_{Other}	.002±.003	.001±.004	2.56	.01	.64	< .001
NDT	896±210ms	888±231ms	.25	*n.s.*	.48	.0004
b	.23±.06	.27±.06	3.97	.0002	.42	.002
d	.0005±.0002	.0005±.0002	.28	*n.s.*	.42	.002

Supplementary Table S2. Association between parameter values, generosity and RT, related to Table 1.

Parameter	Assoc. w/ generosity: $S > $O	Assoc. w/ generosity $S < $O	Assoc. w/ G vs. S RT: $S > $O	Assoc. w/ G vs. S RT: $S < $O
w_{Self}	-2.82**	-1.82**	+.112*	+.137
w_{Other}	+5.69**	+9.56**	+.004	-.312**
NDT	-.28	+.21	+.005	+.09
b	-.94*	-.43	+.075	+.07
d	+.46	+.11	-.007	+.01

** $P < .001$ * $P < .05$

Supplementary Table S3. Regions correlating with stated preferences at the time of choice (GLM 1), related to Figure 3A.

Region	BA	Cluster Size	Z score	x	y	z
L Superior frontal gyrus	10	75	4.9	-12	60	27
B Anterior cingulate cortex	24/32	680	5.37	3	39	18
L Ventromedial prefrontal cortex	11/32	a	5.01	-6	33	-12
R Ventral striatum		a	5.29	9	12	-6
L Ventral striatum		a	5.13	-9	12	-6
L Middle frontal gyrus	6/8	49	4.36	-21	24	54
R Precentral gyrus	6	32	4.33	63	3	24
L Mid-cingulate cortex	24	53	4.27	-3	-6	39
R Supplementary Motor Area	6	16	4.28	6	-12	72
L Precentral gyrus	4	90	4.86	-39	-15	57
L Postcentral gyrus	4	216	5.06	-21	-27	72
R Superior temporal gyrus	21/22	38	4.63	60	-30	6
L Superior temporal gyrus	22/41	179	4.91	-63	-36	9
L Posterior cingulate cortex	31	186	5.64	-6	-42	42
R Inferior temporal gyrus	37	35	5.42	54	-42	-21
L Inferior parietal cortex	7	72	4.48	-36	-75	42
B Occipital cortex	18/19	3430	6.23	-6	-102	0
Occipital cortex	18/19	a	5.3	18	-96	15

Note:
Regions are reported if they passed two thresholds: $P < .0001$ uncorrected and $P < .05$ cluster corrected. A higher threshold was used for reporting because a lower threshold resulted in a single undifferentiated cluster.
a. Distinct peak in larger cluster of activation, reported separately for completeness.

Supplementary Table S4. Neural correlates of $Self and $Other (GLM 2), related to Figure 3B, C.

	Region	BA	Cluster Size	Z score	x	y	z
Regions associated with $Other							
R	Anterior cingulate cortex	24	45	3.82*	9	36	3
L	Inferior parietal lobule/ temporoparietal junction	7/39	217	4.71	-24	-48	24
L	Precuneus	7/31	494	4.89	-9	-60	45
R	Temporoparietal junction	39	63	3.92	39	-63	21
L	Occipital cortex	30	61	4.51	-30	-63	12
R	Occipital cortex	18	76	4.22	21	-90	-9
L	Cerebellum		152	4.24	-24	-93	-27
	Occipital cortex	18	a	4.17	-18	-96	-12
Regions associated with $Self							
R	Anterior cingulate cortex	24	94	5.04	9	36	6
R	Ventromedial prefrontal cortex	32	20	4.13	6	36	-9
R	Inferior frontal gyrus	44	61	4.73	45	0	18
L	Insula	13	20	4.46	-33	0	15
R	Supplementary motor area	6	212	5.1	9	-9	63
L	Postcentral gyrus	3	230	5.33	-48	-18	51
R	Supramarginal gyrus	40	20	4.13	57	-27	27
L	Postcentral gyrus	2	48	4.5	-15	-30	78
L	Mid-cingulate cortex	31	84	4.7	-3	-36	42
L	Superior temporal cortex	41	54	4.76	-51	-36	15
L	Postcentral gyrus	2	47	4.4	-33	-42	66
L	Posterior cingulate	23	13	4.23	-3	-42	21
R	Occipital cortex	18/19	3544	6.73	21	-90	-9
R	Ventral striatum		43	4.79	9	12	-9
Regions where association with $Other > $Self							
R	Temporoparietal junction	39/40	5	3.93†	51	-51	27
Regions where association with $Self > $Other							
R	Anterior cingulate cortex	24	304	4.4	0	39	9
R	Inferior frontal gyrus	44	110	4.48	48	3	15
L	Middle frontal gyrus	6	55	4.32	-48	0	45
R	Supplementary motor area	6	638	5.34	3	-9	54
R	Supramarginal gyrus	40	295	4.53	57	-21	30
L	Postcentral gyrus	3	7849	6.39	-39	-24	54

R	Occipital cortex	18/19	*	5.96	30	-75	21
L	Ventral striatum		32	4.01	-3	-6	6
R	Ventral striatum		208	4.72	9	9	-12
Conjunction of regions associated with $Self and $Other[b]							
L	Occipital cortex	18	244	-	-25	-89	-15
R	Occipital cortex	18	92	-	24	-93	-7
L	Precuneus	7	62	-	-19	-53	36
L	Precuneus	7	52	-	-3	-73	38
R	Mid cingulate cortex	24	50	-	1	9	30
L	Superior frontal gyrus	6	33	-	-22	19	60
L	Frontopolar cortex	10	28	-	-15	65	14
R	Cerebellum		27	-	29	-72	-21
R	Ventromedial prefrontal cortex	24/32	22	-	6	38	9

Note:
Regions are reported if they passed two thresholds: $P < .001$ uncorrected and $P < .05$ cluster corrected. * $P < .05$, small-volume corrected within a-priori ROI. † $P < .005$, uncorrected. a. Distinct peak in larger cluster of activation, reported separately for completeness; b. Maps thresholded separately at $P < .05$, corrected, with minimum overlap of 20 voxels

Supplemental Experimental Procedures.

Alternative specification of the DDM. In the main text, we describe the results of computational model-fitting to the observed data. We observed that a simple model in which choices were determined by five parameters (weights on $Self and $Other, height and collapse rate of a decision threshold, and a non-decision time) was capable of closely reproducing within-subject patterns of variation in choice and reaction times (see section titled "The model accurately predicts out-of-sample choice and RT"). However, we also observed that the fit to these simulations was better for trials on which the proposed amount $Self was higher than $Other, and worse for the trials in which it was lower. We speculated that this difference does not arise from a problem with the DDM per se, but rather may reflect a change in one or more of the parameters of the model when in the domains of advantageous inequality ($Self > $Other) and disadvantageous inequality ($Self < $Other). This distinction has been shown to have a considerable impact on both behaviour and neural response in previous work(Charness and Rabin, 2002; Fehr and Schmidt, 1999; Tricomi et al., 2010) so we sought to address this issue here.

We fit the five parameters of the DDM individually to each subject, using the same method as described in the main text and Online Methods, with the difference that these parameters were fit separately for those trials on which $Self > $Other and trials on which $Self < $Other. We then compared these parameters across the two types of trials to determine both whether there was a systematic difference in one or more parameters between the two trial types, whether there was a correlation across the two models in the parameters fit from the two trial types, and, finally, whether this difference might change any of the conclusions drawn from the simpler model fits.

We quantified the improvement in model fit by using a log-likelihood ratio test (LLRT), where the log-likelihood of each response and RT was estimated using the simulated probability distributions under the best-fitting parameters for each of the two models, and summed over all responses to create the total log-likelihood values L_{Simple} and $L_{Alternative}$. The alternative model has ten degrees of freedom, since it estimates each of the five parameters separately for the two halves of the data, while the simple model, with five degrees of freedom, can be considered a nested version of the alternative in which the parameters for the two trial types are constrained to be equal. Because the simpler model is nested within the more complex one, the distribution of the test-statistic $D = -2 * (L_{Simple} - L_{Alternative})$ is distributed approximately as a χ^2 with degrees of freedom equal to the difference in the degrees of freedom of the two models. We observed a log-likelihood value of -21759 for the simple model and -20873 for the alternative model, yielding a $\chi^2(5) = 885.6$, $P < .001$. Supplemental Figure 1 shows that the model allowing parameters to vary as a function of the relationship between $Self and $Other indeed produced a better fit to the data, although this improvement was more pronounced for choice data than reaction times.

We next examined which parameters of the model changed significantly between the two trial types. These analyses indicated significant differences in three parameters: the weights given to $Self and $Other, as well as the threshold. Trials with disadvantageous inequality showed a higher weight on $Self, a lower weight on $Other, and an increase in the threshold for making a choice (see Supplementary Table S1 for mean and standard deviation for the estimated parameters in the two models, and the results of paired t-tests). Despite this difference, most parameters were correlated across the two halves of the data (see Table S1), with the exception of w_{Self}, suggesting that they likely derived from common processes that persisted across the different trial types.

Multiple regression analyses suggested that individual differences in these parameters correlated in a similar way to observed generosity and RT in the full dataset, although

significance of these parameter values were generally somewhat lower, likely due to the increased noise based on the more limited number of trials. The results of these correlations can be seen in Supplementary Table S2.

fMRI data acquisition. BOLD responses were acquired using a Siemens 3.0 Tesla Trio MRI scanner (Erlangen, Germany) to acquire gradient echo T2*-weighted echo-planar (EPI) images. To optimize functional sensitivity in the orbitofrontal cortex (OFC), a key region of interest, we used a tilted acquisition in an oblique orientation of 30° to the anterior commissure–posterior commissure line. In addition, we used a standard eight-channel phased array coil. Each volume comprised 45 axial slices. A total of 960 volumes were collected over four sessions during the experiment in an interleaved ascending manner. The first two volumes of each session were discarded to allow for scanner equilibration. The imaging parameters were as follows: echo time, 30 ms; field of view, 192 mm; in-plane resolution and slice thickness, 3 mm; repetition time, 2.75 s. Whole-brain high resolution T1-weighted structural scans (1 x 1 x 1 mm) were acquired for the 51 subjects and co-registered with their mean EPI images and averaged together to permit anatomical localization of the functional activations at the group level.

fMRI data pre-processing. Image analysis was performed using SPM5 (Wellcome Department of Imaging Neuroscience, Institute of Neurology, London, UK). Images were corrected for slice acquisition time within each volume, motion corrected with realignment to the last volume, spatially normalized to the standard Montreal Neurological Institute EPI template using affine transformation, and spatially smoothed using an isotropic Gaussian kernel with a full width at half maximum of 8 mm. Intensity normalization and high-pass temporal filtering (using a filter width of 128 s) were also applied to the data.

Instructions given to subjects

Welcome! This is an experiment about decision making. We are interested in understanding how people make decisions about outcomes that affect not only themselves, but also other people. It should take about an hour and 45 minutes, including instructions and a few brief questionnaires. For participating, you will receive at least $30. Depending on your choices during the task, you will have the opportunity to earn from $0 up to $100 more. You will be paid in cash for your time and your earnings at the end of the experiment.

In the experiment room next door, another person is participating, who you should consider your partner. Depending on your choices and the outcomes of some random events, you might end up causing this person to end up with $0 up to $100 more than their pay for participating.

The other person is a real person, and the decision you make can have a large impact on their payoffs. Like you, they signed up for this experiment in response to an email. Since your decisions can have a big impact on their payoffs, think carefully about this other person throughout the experiment.

You will not be told who the person you are matched with is, and this other person will not be told that they were matched with you. They will never be given your name or any information about you.

This means that all choices you make in the experiment should be considered anonymous. Your name will never be connected with the choices you make, and neither your partner nor the experimenter will know what you have chosen.

While your decisions are anonymous, remember: they do have a large impact on the other person's payouts!

The choices you make involve real money, usually quite large amounts, so please think carefully about each decision.

In the next sections, we will describe precisely the instructions for the task you will be doing in the scanner. Pay attention to these instructions. It is critical that you understand the instructions, since they affect your ability to make good decisions – and potentially more money!

Here is how the experiment will work. Every trial will begin with a '+' in the middle of the screen. Please keep your eyes on this center cross when it appears.

After the central cross appears, you will see an offer. On once side of the screen you will see the amount of money you could win if you decide to accept the offer. ON the other side of the screen, you will see the amount of money your partner could win if you accept the offer. We'll call this the *proposed allocation*.

The amounts of money will always range between $0 and $100, for both you and the other person.

If you decide to reject the offer, both you and your partner will each receive $50.

We will call this the *default allocation*, which will be the same for all trials. In every trial, therefore, you are choosing between the proposed allocation and the default allocation.

For instance, if we offer a proposed allocation of $75 for you, $25 for the other person, and you accepted this, this would indicate that you prefer $75 for you ($25 above the default), and $25 total for the other person ($25 below the default).

Although we are asking you to make choice between accepting and rejecting the proposed allocation, we would also like to get a sense of how strongly you feel about this choice. So you should indicate your choice on the following four-point scale:

Strong Yes: Indicates you strongly prefer the proposed allocation to the default.

Yes: Indicates you weakly prefer the proposed allocation to the default.

No: Indicates you weakly prefer the default to the proposed allocation.

Strong No: Indicates you strongly prefer the default to the proposed allocation.

You should respond using the keyboard as follows: [picture of applicable keys]

It is important to note: Either "Strong No" or "No" are counted as choosing the default allocation. Either "Strong Yes" or "Yes" are counted as choosing the proposed allocation. You are still just choosing whether to accept or reject the proposal, but you are also indicating how strongly you prefer the proposed or default options.

One other note: You will be required to make your decision within 4 seconds of the appearance of the proposal. If you do not make a response within that amount of time, *both you and the other person will receive $0 for that trial*.

It is therefore in your best interest to respond in a timely manner according to your preference.

How do your choices on each trial translate into a payment at the end?

At the end of the experiment, we will select *one* trial randomly from among all the trials you saw in the experiment. The results of this trial will count for real money.

Therefore, you should treat every trial when it appears as if it could be the one and only trial that finally determines how much you and your partner receive at the end of the experiment. Because only one trial is selected, your decisions on other trials should not in any way affect what you decide to do on the current trial.

There is one other important detail in this experiment.

Although you will be choosing whether you would prefer the proposed or default allocations, this choice alone will not determine how much money you and your partner would receive if the trial is chosen to count. Once you make your decision, your choice will be *probabilistically implemented*, meaning that the outcome you receive may not always be the allocation you chose.

For every trial, we will pay you and the other person the amount associated with your chosen allocation *60% of the time*. The other 40% of the time, we will implement the allocation you did not choose.

So for instance, if you chose to reject a proposal win which both you and your partner receive $15 ($25 less than the default option), there is a 60% chance that you will both receive the default, which is $50 each, and a 40% chance that you both will only receive $25.

You will find out after your choice on every trial whether we are implementing your preferred option, or the other one.

On trials where your choice is implemented, you will see a green check mark.

On trials where your choice is *not* implemented, you will see a red cross.

On all trials, you will see the amounts that you and your partner will receive if this trial is selected to count at the end of the experiment.

Note: Even though we are probabilistically implementing your choice, your best strategy is still just to choose the allocation you prefer. Most of the time, you will get what you chose, and you always make it more likely to get what you want if you choose it.

Don't let this part of the experiment confuse you: if you prefer the default allocation, reject the proposed offer. If you prefer the proposed allocation, accept the proposed offer instead.

Note also that this probabilistic implementation is NOT based on the choices your partner makes. Rather, it is simply a random lottery that the computer uses to determine whether to implement your choices, or whether to implement the opposite of your choice.

Your partner does not get a say in whether the choice is implemented or not. If that trial is randomly drawn to count for real at the end of the experiment, your partner will simply have to accept whatever the combination of your choice and the probabilistic implementation turns out to be.

You will now have some practice trials. These trials will not count for anything, but are just to give you a sense for the timing and feel of the task. If you have any questions about the task, please ask the experiment *now* Otherwise, please proceed to the practice trials

[Four practice trials were given here]

PRIVACY: As stated earlier, you will be making decisions about how to allocate money between yourself and another person. Importantly, all the decision you make are secret and anonymous. The other person will never know your choices. All they will find out is what the one trial selected to count for real money is, what the proposed and default offers on that trial were, and what the outcome was. They will know that your choices was implemented with 60% probability, but will never see your actual choice.

To make sure your choices are truly anonymous, a computer program will be used to randomly determine which trial counts for payment. The experimenter will put the payment determined by the computer in two envelopes, one for you and one for the other person, but will not know what choice you made on that trial.

You will need to fill out and sign a receipt for your payment. Your signature does not need to be legible. The people handling these receipts do not know anything about the experiment, or about the decisions that can be made in this experiment.

Your partner will be paid in the same way. They will receive an envelope and sign a receipt. Inside the envelope will be their payment as well as the information about the trial: what the proposed allocation on the trial was, and what the final outcome was, but not what your choice was.

Using this setup, no one involved with the experiment will ever know what choices you make. Your partner will not be told who you are, and does not have enough information to link your choices to you.

All of the data about your choices will be identified by an anonymous code that will have no connection to your personal information. The previous sections explain the careful procedures we use to make sure of this.

This experiment will produce valid results only if you believe that your decisions are anonymous and secret. This is why we take these issues extremely seriously! We are bound ethically and legally to keep the promises we are making to you in this protocol. We are not allowed to use any deception in this experiment. We will do everything we say, and there not be any surprises or tricks.

If you have any questions about the experiment, please ask the experiment now.

Again, it is important that throughout this experiment, you consider both your feelings about the transfer and the potential impact on the other person. Your decisions can have a big impact on the payment they receive for the experiment, so consider both the pros and cons of each of the transfers.

Take your time! There are a number of transfers to consider, and each has both pros and cons. Try to think carefully about what the other person would in your shoes and how you might feel about the outcome.

Before you being, we would like to ask you a few questions to make sure that you have understood the task. We will ask you to determine the final payoff to you and your partner under different conditions.

Press any key to continue to the short quiz.

[3 quiz questions to ascertain comprehension of the instructions given here.

Following completion of the quiz, and clarification by the experimenter of any questions that were missed, the participant began the scanning session.]

Supplemental References

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