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Neurocomputational mechanisms engaged in detecting cooperative and competitive intentions of others

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29 **Abstract**

30 Humans frequently interact with other agents whose intentions can fluctuate over time between
31 competitive and cooperative strategies. How does the brain decide whether the others' intentions are
32 to cooperate or compete when the nature of the interactions is not explicitly signaled? We used model-
33 based fMRI and a task in which participants thought they were playing with another player. In fact, this
34 agent was an algorithm alternating without signaling between cooperative and competitive strategies.
35 A neurocomputational mechanism underlying arbitration between competitive and cooperative experts
36 outperforms other learning models in predicting choice behavior. The ventral striatum and ventromedial
37 prefrontal cortex tracked the reliability of this arbitration process. When attributing competitive
38 intentions, these regions increased their coupling with a network that distinguish prediction error related
39 to competition *versus* cooperation. These findings provide a neurocomputational account of how the
40 brain dynamically arbitrates between cooperative and competitive intentions when making adaptive
41 social decisions.
42

43 Introduction

44 During social interactions, humans are often uncertain whether others intend to compete or
45 cooperate. The intentions of other agents can fluctuate over time, making it challenging to develop
46 behavioral strategies. A key question is to understand how the brain decides whether the other is
47 cooperating or competing during volatile situations in which the nature of the social interactions is not
48 explicitly determined, as when others interact to achieve a common goal while maximizing their own
49 benefits. This question is of importance since it lies at the heart of strategic social decision making ^{1–9}.
50 In these types of situations, other agents can change behavior according to cooperative or competitive
51 intentions. Cooperation is generally defined as involving a group of individuals working together to attain
52 a common goal ^{10,11}. In contrast, competition involves one person attempting to outperform another in
53 a zero-sum situation ¹². A number of theoretical accounts and experimental results demonstrate that
54 the ability to mentalize, i.e. to simulate the other's belief about one's next course of action, is crucial for
55 strategically sophisticated agents ^{6,7,13,14}. The neurocomputational mechanisms engaged in attributing
56 intentions to others has been studied in situations in which participants are explicitly informed about the
57 nature of the interactions, either in a collaborative context alone ^{15–17} or in a competitive context alone
58 ^{8,18–25}. For example, during a cooperative game such as the coordination game, one of the best
59 strategies is to try to choose one of two presented targets consistently. In contrast, in a competitive
60 game such as the matching pennies game ^{19,25}, the optimal strategy is to choose between two targets
61 equally often and randomly across trials. If the identity of the game played is not known, the agent has
62 to adjust his/her strategy based on repeated interactions with others and to infer
63 cooperation/competition on the basis of observations. How the brain achieves such inference poses a
64 unique computational problem because it not only requires the recursive representation of reciprocal
65 beliefs about other's intentions, as in cooperative or competitive contexts alone, but it also requires one
66 to decide whether the other is competing or cooperating to deploy an appropriate behavioral strategy.

67 Here, we sought to determine the neurocomputational mechanisms that underlie the inferences
68 of whether a person is competing or cooperating during volatile situations in which the nature of the
69 interactions is not explicitly signaled. A recent computational account proposed that arbitration between
70 strategies is determined by their predictive reliability, such that control over behavior is adaptively
71 weighted toward the strategy with the most reliable prediction ²⁶. This approach has been tested
72 successfully in the domains of instrumental or Pavlovian action selection ²⁷, model-based and model-
73 free learning ²⁸ and learning by imitation or emulation ²⁹. Extending this concept of a mixture of experts
74 to social interactions, we investigated whether the brain relies on distinct experts to compute the best
75 choice between two possible intentions attributed to others (cooperation or competition) and then
76 weights them by their relative reliability. We tested and compared these mixtures of models, that
77 attribute intentions to others dynamically, with different classes of learning models: non-Bayesian vs
78 Bayesian and non-mentalizing vs mentalizing (**see table 1**). This allowed us to identify the algorithms

79 and brain mechanisms engaged with a key component of the estimation of other's intentions, i.e.
80 whether the social partner was cooperating or competing.

81 The majority of theoretical frameworks used to model feedback-dependent changes in decision
82 making strategies, such as choice reinforcement and related Markov Decision Process (MDP) models,
83 assume that optimal decisions can be determined from the observable events and variables by the
84 decision makers. Clearly, these assumptions do not capture the reality and complexity of human social
85 interactions because observable behaviors of other individuals provide only very partial information
86 about their likely future behaviors. Moreover, model-free RL algorithms assume that values (utility or
87 desirability of states and actions), change incrementally across trials. This assumption is incorrect when
88 option values change abruptly, such as when the intention of the other shifts between cooperation and
89 competition. These limitations explain why agents basing their behavior only on standard RL models
90 can be exploited by opponents using more sophisticated algorithms ^{6,30}.

91 A more accurate account of strategic learning is based on a family of RL models which adds a
92 mathematical term to the classical Temporal Difference (TD) algorithm to consider the other as an agent
93 having their own policy, which can be influenced by oneself ^{6,30,31}. For example, fictitious play learning
94 proposes a basic form of mentalizing by having a representation of the other's strategy. Influence
95 models also consider that RL can be supplemented by a mentalizing term that represents how our
96 actions influence those of others, updated through a belief prediction error ^{2,6,19,21,30,32–34}. Such influence
97 models formalize not only how players react to others' past choices, (first-order beliefs in Theory of
98 Mind: ToM), but also how they anticipate the influence of their own choices on the others' behavior (i.e.,
99 mentalizing-related second-order beliefs). Another modeling approach of theory of mind used Bayesian
100 algorithms to model inferences about the future actions of another, attempting to take their point of view
101 and to simulate their decision ^{13,17,35}. This strategy can be performed recursively so that participants
102 make inferences concerning the others' inferences and so on. Such a sophisticated approach could be
103 grounded in the theoretical framework of Partially Observable Markov Decision Processes (POMDPs)
104 ³⁶. POMDPs provide a probabilistic framework for solving tasks involving action selection and decision
105 making under uncertainty ^{37,38}. Notably, this approach has recently been applied to strategic cooperation
106 in groups ^{36,39,40}. These models, however, have mainly been limited to signaled cooperative or
107 competitive tasks where the intentions of players do not change over a given period ^{13,35,41,42}.

108 Here, we tested the predictions of these different families of learning models against one
109 another, investigating not only non-Bayesian vs Bayesian models and non-mentalizing vs mentalizing
110 models, but also a mixture of models deploying an arbitration process whereby the influence of
111 attributing intentions to others is dynamically modulated depending on which type of intention (i.e.
112 cooperative vs competitive) is most suitable to guide behavior at a given time. We did so by using a
113 novel model-based fMRI design (**Fig. 1**) consisting of an iterative dyadic game in which participants
114 were told that they would interact with another person via a computer. Unbeknownst to them, the other

115 player was an artificial agent that switched between blocks of cooperative trials and blocks of
116 competitive trials when playing a card matching game. Thus, the algorithm's goals were the same as
117 those of participants in the Cooperative blocks but were orthogonal in Competitive blocks. Participants
118 remained uncertain with respect to the goals of their "partner" or "opponent", which alternated, without
119 being signaled. This task allowed us to investigate the algorithms used by the brain to recognize the
120 "intentions" of others and to adopt appropriate strategies when the modes of interaction (cooperation
121 vs competition) are not indicated.

122 We found that the model accounting best for behavior was a mixture of influence models,
123 referred to as Mixed-Intention Influence Model. Two expert systems work together to make strategic
124 decisions, one assessing competitive intentions and the other assessing cooperative intentions, a
125 controller weighting between these experts according to their relative reliabilities. Each expert system
126 uses a classic RL algorithm complemented with a mentalizing term to infer the other's actions. This
127 Mixed-Intention Influence model accounts for behavior observed in naturalistic environments in which
128 the other's goal is often only partially congruent with one's own, allowing for a continuous range of
129 behavior between pure cooperation and pure competition. A brain network including the ventromedial
130 prefrontal cortex (vmPFC) and the ventral striatum tracked the reliability signal from the controller. This
131 finding indicates that the Mixed-Intention Influence model captures the higher-order structure of the
132 mixed-intentions task (i.e., alternation between cooperation and competition). When comparing trials
133 classified as competitive versus cooperative by the controller, we also identified a brain system engaged
134 with an updating signal used for learning. Finally, when participants expected higher utility for choosing
135 according to a competitive rather than cooperative strategies, the vmPFC and the ventral striatum,
136 tracked the intentions of others and showed changes in functional connectivity with a brain system
137 including the right temporo-parietal junction (rTPJ), dorsolateral prefrontal cortex (dlPFC) and the intra-
138 parietal sulcus (IPS), which discriminates reward prediction error (PE) between believed modes of
139 interaction. Together, these results provide a model-based account of the neurocomputational
140 mechanisms guiding human strategic decisions during games in which the intentions of others fluctuate
141 between cooperation and competition.

142

143 Results

144 Behavioral signature of tracking intentions

145 We assessed how participants used the history of previous interactions to make their choices.
146 We used logistic regression to examine whether participants selected the same target as that from the
147 previous trial (“Stay”) or chose the other target (“Switch”), depending on whether the previous three
148 trials (at $t-1$, $t-2$ and $t-3$) had been won or lost, whether the previous decisions had been to Stay or
149 Switch, and whether the previous interactions from those trials indicated cooperation (see below). We
150 also added sex, age and the number of trials as control variables. All trials except the 5 initialization
151 trials were included in this analysis. Cooperation was defined by a binomial variable, representing the
152 interaction between the last action of the Artificial Agent (AA) and the participant’s own previous
153 outcome (“Cooperativity signature”). This variable was set to 1 if either the participant had won on the
154 previous trial and the AA stayed on the same target for the next trial, or if the participant lost on the
155 previous trial and the AA switched to the other target the trial just after. Otherwise, the variable was set
156 to 0. Indeed, from the perspective of the participant, if the AA is a cooperative partner, both players win
157 at the same time and should then choose to keep the same target to be more predictable.

158 We found that the “Cooperativity signature” predicted an increase in the “stay” probability of
159 participants at $t-1$ and $t-2$ (Cooperativity signature $_{t-1}$: *estimate* = 0.05, $p=0.021$;
160 Cooperativity signature $_{t-2}$: *estimate* = 0.05, $p=0.002$, χ^2 test **Fig. 2a**). This suggests the participants
161 tracked whether the other agent was cooperating during the two previous trials (but not before).
162 Participants used the outcome of the latest trial to make the next decision (staying or switching target)
163 according to a win/stay, lose/switch strategy (winning $_{t-1}$: *estimate* = 0.16, $p<0.0005$, χ^2 test **Fig. 2a**).
164

165 Computational models tracking intentions of the other agent

166 To elucidate the computations underlying strategic decision making, we compared the results
167 of different computational models. These models were split into five classes (**see SI**). The first class of
168 models, based on heuristics, included Win-Stay/Lose-Switch and Random Bias models. The other four
169 classes of algorithms can be classified into non-Bayesian *versus* Bayesian model families along one
170 dimension and mentalizing *versus* non-mentalizing model families along the other dimension. Thus, the
171 second class of models includes non-Bayesian, non-mentalizing models represented by reinforcement
172 learning (RL) models. The third class represents non-Bayesian mentalizing models, namely the
173 “influence models” which are RL models with an additional term representing how the actions of one
174 player influence those of the other player. The fourth class corresponds to Bayesian non-mentalizing
175 models, including (1) a Hierarchical Gaussian Filter (HGF) which tracks the volatility of outcome⁴³, (2)
176 the k -Bayesian Sequence Learner which tracks the probability that one target will be selected by the
177 AA after a history of specific length k and (3) the *active inference* model which minimizes the expected

free energy⁴⁴. The fifth class of models contains Bayesian mentalizing models, which are the k -ToM models using recursive Bayesian inferences of depth k to predict the future choice of the AA. Each mentalizing model was tested using 3 versions: a competitive, a cooperative and a ‘mixed intentions’ version. The ‘mixed intentions’ version computes one decision value according to a competitive expert and another according to a cooperative expert and arbitrates between the two, based on the difference in their respective reliability (see SI, Fig. 3a). We defined reliability as the difference in unsigned value functions for two choices given by particular learning algorithms.

Next, we performed a group-level random-effect Bayesian model selection on the models’ computed free energy, taking into account potential outliers and the number of free parameters^{45,46}. We found that the ‘Mixed Intentions Influence Learning’ Model was the most frequent best fit across the population (Fig. 2b), demonstrating that subjects employed mentalizing-related computations in our mixed intentions task. This finding also indicates that arbitration between a cooperative and a competitive expert best explains most participants’ behavior, rather than either expert taken individually. Additionally, only the Mixed-Intention Influence model (and not the cooperative or the competitive one) succeeded in producing behavior, similar to participants, with respect to the effect of the Cooperativity signature on the probability to stay (Fig. 3b and Extended Fig.1, see SI). We conducted a logistic regression to understand how the Mixed-Intention Influence model explained differences in behavioral strategy to stay or switch target. This analysis included the reward prediction error at $t-1$, the valence of the arbitration between cooperative and competitive intention at time t ($\text{sign}(\Delta)$; 1 for cooperative and -1 for competitive), and the interaction between these two variables. This analysis revealed a main effect of the valence of the arbitration ($\text{valence of the arbitration}_t : \text{estimate} = 0.24, p < 0.0005, \chi^2$ test Fig. 3c) indicating that participant tend to stay more on the same target when they attributed cooperative intention to the other. Moreover, we found an interaction effect, i.e. participants did not integrate the prediction error in their strategy in the same way given the attributed intention ($\text{valence of the arbitration}_t * rPE_{t-1} : \text{estimate} = 0.20, p = 0.0227, \chi^2$ test Fig. 3c). That is, higher negative prediction errors increased the probability that the participant would stay on the same target when the controller attributed cooperative intentions compared to when it attributed competitive intentions. In addition, we also performed another logistic regression analysis using the same variables and the actual mode of interaction (i.e. competitive block trials *versus* cooperative block trials), rather than the classified mode of interaction made by the controller. We did not find the same interaction effect when we compared actual competitive and cooperative block trials ($\text{Block type}_t * rPE_{t-1} : \text{estimate} = 0.003, p = 0.56, \text{Block type}_t : \text{estimate} = 0.03, p = 0.229, \text{and } PE_{t-1} : \text{estimate} = 0.14, p < 0.0005, \chi^2$ test; Extended Fig.2, see SI), showing that the classified intentions, but not competitive or cooperative blocks, affected the use of prediction error.

We reasoned that when facing an individual who can change his/her intentions to compete or cooperate over time, the brain may rely on distinct experts to compute the best choice based on these

two possible intentions (i.e. cooperative or competitive), weighted by their relative reliabilities. We therefore built such an ‘arbitrator’ computation as a sigmoid function of the difference in reliability between the Cooperative and Competitive interactions (Δ), added to a bias (δ) that characterized each individual’s tendency to attribute competitive ($\delta > 0$) or cooperative ($\delta < 0$) intentions to others. To assess intentions of the other, participants only have access to the outcomes of previous interactions, the choice (to stay or switch) of the artificial agent on previous trials, and the interaction between these two types of information.

We hypothesized that repeated social victories should favor the attribution of cooperative intentions because a series of victories suggests that both players are satisfied with the outcome. In such situations the other player (i.e. AA) has become more predictable, which is an important feature to build cooperation⁴⁷. Moreover, the interaction between outcome and AA’s choice (i.e. the tendency of the AA to “stay” after a participant wins or “switch” after a participant loses) should drive the arbitrator to favor the cooperative mode, because playing the same winning target for both players corresponds to the optimal Nash equilibrium of the cooperative game. To test this hypothesis, we regressed the signed difference in reliability on (1) the participant’s last outcome, (2) AA’s choice to “stay” or to “switch” and (3) the interaction between the participant’s outcome and the AA’s choice to stay or switch (Cooperativity signature) over up to three retrospective trials. We found that the past two interactions between participant’s outcome and AA’s action (Cooperativity signature), the last outcome and switches by the AA at trial $t-2$ and $t-3$ explained the difference in reliability (*Cooperativity signature* $t-1$: *estimate* =0.59, $p < 0.0005$; *Cooperativity signature* $t-2$: *estimate* =0.06, $p = 0.037$; *Victory*: *estimate* =1.98, $p < 0.0005$; *switch* $t-2$: *estimate* =-0.18, $p < 0.0005$; *switch* $t-3$: *estimate* =-0.07, $p < 0.0005$), χ^2 test, **Fig. 4a**).

Together, these analyses show that participants’ behavior, when alternating between unsignaled cooperative and competitive blocks, is best explained by the Mixed-Intention Influence model. According to these findings, people use mentalization to update their beliefs about future chosen targets, and dynamically arbitrate between the predicted intentions of the other agent to compete or cooperate (**Fig. 3a**).

242

243 **Model-based fMRI analyses**

244 First, we constructed a GLM (GLM1) to identify brain regions tracking the arbitration process
 245 (i.e. Δ : signed reliability difference, reliability for cooperation minus that of competition) between the two
 246 experts (one for cooperation, the other for competition). We added the reliability difference Δ as
 247 parametric regressor at the decision stage, and the expected reward for staying on the same target, as
 248 non-orthogonalized parametric regressors to allow them to compete for the variance. We added the

reward prediction error as a parametric regressor at the outcome time and we controlled for the other's intention effect by adding Δ as a non-orthogonalized regressor. The bilateral ventral striatum (x,y,z=9,12,0 and x,y,z=-12,9,-6,), vmPFC (x,y,z=6,45,-8), postcentral gyrus (x,y,z=-20,-44,48), and middle cingulate cortex (MCC; x,y,z=11,-15,57, $p<0.05$ whole-brain family-wise error (FWE), **Fig. 4b and 4c**) tracked the difference in reliability between experts (Δ) at the decision time. Bilateral dorsal striatum (DS; x,y,z=17,6,-12 and -14,3,-11), bilateral orbitofrontal cortex (OFC; x,y,z=44,36,-14 and -44,36,-14), posterior cingulate cortex (PCC; x,y,z=2,-34,38), and bilateral angular gyrus (x,y,z=45,-30,46 and -54,-62,39) ($p<0.05$ FWE, **Fig. 5a**) encoded the reward prediction error at the outcome time.

To investigate brain areas encoding the reward prediction error that were more engaged when the controller classified a trial as competitive vs cooperative, we tested another GLM (GLM2). Trial onsets were separated according to whether the value of the signed reliability difference Δ added to the bias was positive or negative. If this value was ≥ 0 , the trial was classified as Cooperative, and Competitive otherwise. The computed expected reward for staying on the same target was used as a parametric regressor at the time of choice. We found that the right dlPFC (x,y,z=35,11,36), the IPS region (x,y,z=50,-50,32) and the right temporoparietal junction (rTPJ; x,y,z = 51,-50,33, $p<0.05$ FWE) were more engaged in encoding reward prediction error in trials classified as Competitive versus Cooperative ($p<0.05$, FWE **Fig. 5b and 5c**). This effect could not be explained by less variance in the PE regressor in trials classified as Competitive trials compared to those classified as Cooperative, because we observed no difference in regressor variance on these two types of trials ($p=0.57$, Levene's test). No region was more engaged in trials classified as Cooperative compared to those classified as Competitive.

To further investigate the relationship between the behavior to stay after a trial classified as Competitive *versus* classified as Cooperative and the BOLD signal, we conducted a logistic regression. Explanatory variables were the average of the weighted time series in the dlPFC and rTPJ/IPS region observed in GLM2, the valence of the controller (Δ) and their interactions. This signal was extracted at the time of the outcome and convolved with the hemodynamic function. Because there was an average of 6.6 scans per trial, we took as a predictor variable the mean of this weighted signal through the 7 scans following the outcome presentation. We found an interaction between the weighted time series and the valence of the arbitration (*valence of the arbitration_t * weighted time series_{t-1} : estimate = -14.4, $p = 0.0312$, χ^2 test*). *Post hoc* tests further revealed that this effect was driven by trials classified as Competitive (*weighted time series_{t-1} of trial classified as competitive_{t-1} : estimate = -37.3, $p = 0.040$, χ^2 test*). This result indicates that activation of dlPFC and rTPJ/IPS increases the probability of switching following a trial classified as Competitive.

$$\text{logit}(P(\text{stay})) = \beta_0 + \beta_1 * \text{sign}(\Delta) + \beta_2 * \text{Time Series} + \beta_3 * \text{sign}(\Delta) * \text{Time Series}$$

284 **Connectivity analysis**

285 Finally, we performed a generalized psycho-physiological interaction (gPPI) seed to voxels
286 connectivity analysis to understand the interactions between brain regions tracking the arbitration
287 process (i.e. Δ : reliability difference) for the cooperative and competitive experts and those more
288 engaged with the PE when the controller attributes more competitive than cooperative intentions to the
289 other (**see Online Methods**). We used the ventral striatum and vmPFC, which encoded the controller,
290 as seed regions (ROI extracted from the GLM1 striatal and vmPFC activity) for trials classified as
291 competitive compared to those classified as cooperative (i.e. trials for $\Delta < 0$ or $\Delta > 0$) at the decision time.
292 We found stronger functional connectivity between regions encoding the difference in reliability and the
293 right dlPFC (x,y,z=38,34,34), the left IPS region (x,y,z=-48;-44;58) and the left TPJ (x,y,z=-42,-40,50,
294 $p < 0.05$ FWE; **Fig. 6a**) at the decision time for trials classified as Competitive compared to those
295 classified as Cooperative. This result indicates that the dlPFC, IPS and left TPJ receive an input signal
296 at the time of choice according to the difference in reliability with respect to the Competitive *versus*
297 Cooperative believed intention of others. This brain network largely overlaps with the brain network
298 observed with the PE differentiating between trials classified as Competitive *versus* Cooperative at the
299 outcome (**Fig. 5b** and **Extended Fig. 4**).

300

301 Discussion

302 To make a strategic decision when facing an individual with unknown and fluctuating intentions,
303 it is necessary to make inferences as to whether we are in a competitive or cooperative situation. In the
304 context of minimal information, for example when only the choices of the other, but not their outcomes,
305 are available, such inferences are much more difficult than when one is in a specific known setting (e.g.,
306 in a competitive game) ¹⁹. Here, we provide evidence that the brain engages in dynamic tracking of
307 another individual's cooperative/competitive intentions, despite having no explicit information regarding
308 whether the situation is cooperative or competitive. We found that strategies of participants were mostly
309 affected by the outcomes of previous interactions and by a "signature" of the other's cooperativity, i.e.
310 the tendency of the other (here the Artificial Agent or AA) to stay on the same target after the
311 participant's winning. Comparison between computational models demonstrated that such behavior is
312 best explained by a model in which choice is driven by a controller tracking the reliability difference
313 between cooperative and competitive intentions. The fMRI results show that the neural computations
314 of this controller are implemented in the ventral striatum and in the vmPFC. Thus, both behavior and
315 brain imaging results can be accounted for by a model that includes a controller that allocates resources
316 according to different experts' predictions. At the time of outcome, a common brain network, including
317 the rostral anterior cingulate cortex (rACC), ventral striatum and lateral OFC encoded prediction error
318 in trials classified as Competitive or as Cooperative. However, prediction error signals in some brain
319 areas also depended on the classification of the current trial as Cooperative or Competitive as classified
320 by the controller. That is, a distinct brain network, composed of the bilateral dlPFC, bilateral IPS regions
321 and the rTPJ was more engaged for trials classified as Competitive compared to those classified as
322 Cooperative. This latter brain network reflects a differential use of the outcome of the social interaction
323 as a function of whether it is classified as Competitive or Cooperative (**Fig. 2d**).

324 Mentalizing processes are essential to correctly infer the strategy of others. This is true in the
325 cooperative context, in which participants performed above chance, reflecting their ability to effectively
326 infer the other's (i.e. AA's) behavior. In the competitive context, participants performed below chance
327 level, showing that the AA was able to predict their behavior and to exploit their previous
328 choices/outcomes. The Mixed-Intention Influence model had the best ability to predict data and to
329 generate very similar behavior to the participants. Each expert model is an expanded RL model, with a
330 term accounting for one's previous choice influencing the choice of the other. Although only the
331 influence term differed between the Competitive and Cooperative models, the Mixed-Intention Influence
332 model tracked intentions based on this second order mentalizing term by weighting the contribution of
333 a cooperative and of a competitive expert. One key aspect of this Mixed-Intention Influence model is
334 that it captures higher order structures (fluctuations between cooperation and competition) during social
335 interactions. In contrast, one important limitation of the classical RL model is that it does not exploit
336 higher-order structures such as interdependencies between different stimuli, actions, and subsequent

rewards. Previous studies demonstrated that models incorporating such structures can account for individual decision making in different situations ^{48–51}. Here, we demonstrate that the representation of abstract states, such as whether the other is cooperating or competing, can be extended to social decisions and underlies the ability to build strategies. To confirm that the Mixed-Intention Influence model accounted more for neural activity in brain areas involved in social interactions, we formally compared the brain regions covarying more with the expected reward for staying on the same target, as computed by the winning model, compared to the expected reward for staying on the same target, computed by a simple RL model (**Extended Fig. 3**). One crucial difference between a simple RL model and the Mixed-Intention Influence model is that in the former, only the value of the chosen option is updated and the valuation of the option that was not chosen does not change. In the latter, both the values of the chosen and unchosen options are updated to incorporate the knowledge that the current state has a given reliability to be cooperative or competitive. The controller weights the valuation produced according to the competitive or cooperative hypothesis which is computed as a sigmoid of the difference in reliability between the two experts.

Activity in the ventral striatum and vmPFC increased as the cooperative prediction from the controller became more reliable than the competitive prediction, as a result of the outcomes of the previous interactions (reliability difference modulated by last outcome) and the other's "Cooperativity signature" over the last trials. Thus, these brain regions dynamically track the reliability difference between intentions classified as cooperative and competitive in a situation where the nature of the social interactions is implicit. Previous reports demonstrated a role of the ventral striatum when making cooperative choices alone, in response to a partner's cooperative choice in an explicit cooperation task ⁵² and also in the attribution of intentions in a competitive context ³⁰. Our findings show that strategic social behavior can be explained by a Controller Theory according to which cooperative/competitive social behavior results from the interaction of multiple systems, each proposing possible strategies for action ^{26,28,29}.

One strength of our computational approach was to assess and compare a large variety of competing models, (active inference, recursive learning models k-TOM and a mixture of experts using k-TOM, influence models for only cooperative strategies or competitive strategies, a mixture of experts using influence models, fictitious learner, Bayesian Sequence learner, Hierarchical Gaussian Filter, Reinforcement Learning and Heuristic models). Many have never previously been directly tested against each other. Our results agree with studies concluding that social learning may be driven by non-specific reinforcement processes that include a mentalizing term ^{3,6,8,30,53}. We demonstrate that when a task is not explicitly signaled as cooperative or competitive, this evokes the arbitration between strategies determined by predictive reliability. Behavior is hence controlled by giving a higher weight to the strategy with the most reliable prediction ²⁹. At first glance, it may be surprising to observe that the mixture of expert influence models performs better than mathematically more sophisticated models,

such as POMDP models (HGF, active inference, k-ToMs) and models mimicking different levels of mentalizing (k-TOM). However, this is likely because in our setting the only information that can be integrated by participants is their own choices, rewards and the history of the choices made by the other (i.e. AA). The nature of the social interaction is never explicitly signaled (participants are not told whether the other is cooperative or competitive), and the rewards of the other are not observed. This uncertainty could therefore result in the failure of POMDP models to reproduce human behavior, particularly when sudden flips occur between the AA strategies. This contrasts with previous neuroimaging studies that investigated learning of social interactions in either competitive or cooperative situations alone (matching-pennies or rock-paper-scissors games against computerized opponents)^{25,54}. Our findings also broadly agree with a cognitive hierarchy of strategic learning mechanisms, proposing that distinct levels of strategic thinking correspond to different levels of sophistication of learning mechanisms (in increasing order of complexity: reinforcement learning, fictitious play learning and influence learning)⁵⁵. However, we propose a more general model based on a mixture of influence learning experts that function in parallel and are then compared with respect to their relative reliability.

Competitive social interactions often emerge in situations where an agent's outcome depends on the choices of others, which requires the ability to infer the intentions of others⁶. In the context of our mixed intentions task, when participants attributed competitive, as opposed to cooperative intentions to others, the dlPFC and rTPJ/IPS specifically encoded a relative PE. Although this network has previously been reported when inferring the intentions of others^{8,39,56}, the strength of our computational account of theory of mind processes is to specify that this brain network computes a PE difference between trials that the controller classified as competitive *versus* cooperative. This PE difference reflects a differentiation in the implementation and use of the outcome of the social interaction as a function of the classified interaction (**Fig. 3c**). Note that PE was not more volatile in trials when the competitive expert is more reliable than the cooperative expert. This rules out the possibility that the observed PE difference reflects higher PE volatility in competitive contexts. When comparing intentions classified as cooperative compared to competitive, participants tended to be more predictable, staying more on the same target after experiencing an unexpected social defeat (i.e. after higher negative PE) (**Fig. 3c**). This behavior likely reflects a signal sent to the other to indicate one's willingness to stay on the same target, despite bearing the cost of staying on this target^{6,8,57}. This is a key feature of successful coordination⁴⁷ in which agents who want to trigger reciprocity⁵² are willing to incur a cost to promote cooperation from the other.

Finally, we found higher functional connectivity between seed regions that encode the reliability difference of the controller (vmPFC and striatum) and brain regions more engaged in PE for trials classified as Competitive *versus* Cooperative (dlPFC, TPJ) (**Fig. 6**). This indicates that brain regions engaged in the input of the arbitration process at the time of choice are more strongly coupled (resp. decoupled) with brain regions encoding PE for intentions classified as Competitive (vs Cooperative).

409 This reflects a differential use of the outcome of the social interaction as a function of whether it is
410 classified as Competitive or Cooperative. Thus, according to the attributed intention of other by the
411 controller, PE signals differed and the strength of functional coupling increased between regions
412 encoding the reliability difference of the controller and the dlPFC-TPJ network. When one expert is
413 more reliable than the other, the Mixed-Intention Influence model predicts that the reward PE is driven
414 by the valuation of the more reliable expert. Since the only difference between experts is the sign of the
415 second-order mentalizing term, this suggests that the implication of the dlPFC-TPJ network at the
416 outcome is engaged when there is a need to mentalize intentions of other agents with opposing goals
417 (i.e. intentions classified as Competitive). Moreover, engagement of the dlPFC-TPJ network increases
418 the probability of switching following a trial classified as competitive by the controller, allowing
419 behavioral adaptation by virtue of the reliability difference signal.

420 Together, our work provides evidence that the mixture of experts model explains behavior in
421 socially volatile situations differing only by the reward function of other agents. These two experts only
422 differ by their priors on how their reward function takes into account another agent's reward (i.e. the
423 second order mentalizing term), and were sufficient to discriminate the others' intentions. These findings
424 provide a mechanistic framework explaining the neurocomputations underlying learning in strategic
425 social interactions. We extend to theory of mind processes (i.e inferring cooperative vs competitive
426 intentions) a computational account similar to mixture of experts proposed to arbitrate between
427 strategies in other domains, such as exploitation vs exploration ^{58,59}, "model-based" vs "model-free"
428 systems ^{26,28,60} and learning by imitation vs emulation ²⁹. Finally, our Mixed-Intention Influence model
429 may be useful in the field of computational neuropsychiatry to identify the specific computational
430 components that are modified in theory of mind alterations, a key feature of autism spectrum disorder
431 ⁶¹.

432

433 **Author contributions**

434 J.-C.D., R.P., R. P.N.R., and D.L. developed the general concept, experiment and models. R.P.
435 programmed the task and ran the experiment under the supervision of J.-C.D. R.P. developed the
436 models and implemented the algorithms under the supervision of J.-C.D., and analyzed the data in
437 collaboration with J.-C.D. R.P. and J.-C.D. wrote the manuscript in collaboration with K.K., D.L. and
438 R.P.N.R.

439

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449

450 **Competing interests**

451 The authors declare that they have no competing interests.

452

453 **Resources availability**

454 **Lead contact**

455 Further information and requests for resources and inquiries should be directed to and will be
456 fulfilled by the lead contact, Jean-Claude DREHER (dreher@isc.cnrs.fr).

457 This study did not generate new unique reagents.

458 **Materials availability**

459 This study did not generate new unique reagents.

460 **Data and code availability**

461 Code supporting main results are available at GitHub
462 (https://github.com/remiphilipp/Mixture_intention.git).

463 **Method**

464 **Participants**

465 32 participants (aged 20-40, $M = 27$, $SD = 5.1$ - 17 women) were recruited via a daily local
466 newspaper and the University of Lyon 1 mailing list. All participants were screened to exclude those
467 with medical conditions including psychological or physical illnesses or a history of head injury to
468 prevent having confounding variables. They all provided informed consent and were paid a fixed
469 amount. However, they were financially motivated in being told that they would be paid as a function of
470 their decisions.

471 **Mixed intentions task**

472 Participants performed a novel task comprising 163 trials in an MRI scanner. They were led to
473 believe that they were interacting with another person via a computer interface, while in fact they were
474 playing against an artificial agent (AA) managed by a computer program. Such simulated social
475 interactions allowed us to investigate the dynamics and neural mechanisms arbitrating between multiple
476 learning algorithms. Participants were faced with a screen containing four cards, two face down (the
477 other player's cards) and two face up (their own cards). Participants were informed that to win, they had
478 to choose the card of the same color as the one the other person was going to choose. Experimenters
479 were careful not to specify whether the other was an adversary or a partner. Participants were told that
480 they and the other player had to make their choices in four seconds (**Fig. 1a**). If the Artificial Agent (AA)
481 played before the participant, one of the two face down cards was removed from the playing field. If the
482 participant chose first, only the selected card remained on the playing field. Then, when both had
483 chosen, the chosen cards were revealed and the participant received a reward if the card colors
484 matched, otherwise they received nothing. Participants were led to believe that their final payoff would
485 be increased by 10 ct (euro) for each winning interaction. No information about the other's payoff was
486 given to the participants, they only knew that after an interaction, the other 'participant' would see the
487 same screen but with their outcomes which could be different from the participant.

488 Importantly, unbeknownst to the participants, the artificial agent alternated between Competitive
489 and Cooperative trial blocks. During this mixed intentions task, the AA's strategy was determined by
490 alternating 13 trials of a hide and seek (HS) task (Competitive blocks), and 10 trials of a coordination
491 game (Cooperative blocks). The artificial agent algorithm was designed to predict the color that would
492 be chosen by the participant on the basis of a probabilistic analysis of the two previous choices and
493 outcomes (**see SI** for the algorithm). Here we defined a competitive choice, made by the AA, as
494 choosing the card of the color the participant was expected not to play and a cooperative choice as
495 choosing the card with the same color. Thus, the artificial agent exploited the bias of the participants in
496 a stochastic way, i.e. the more predictable the participant was, the more the algorithm made correct
497 competitive or cooperative choices (see SI). Participants were not informed of the switches between

the two blocks (Cooperative vs Competitive), however their goal was always to choose the same color as that chosen by the other player (i.e. the AA).

The HS task is competitive, and the computer uses the record of the participant's choice and reward history to minimize the participant's payoff. Therefore, in this case the subject's optimal strategy during the HS task is to choose the two targets equally often and randomly across trials. During the coordination game, the AA tried to maximize the subject's payoff and in this case the subjects should try to choose one of the two targets consistently so that the computer can choose the same target as them. Since the participant is not informed of either the goals of the AA or the switches between blocks, they must adjust their strategy based on recent experience and infer cooperation/competition on the basis of their observations.

This task was designed to identify key components of the estimation of intentions regarding whether others are cooperating or competing. We took advantage of the fact that an individual's estimates as to whether they are engaged in a cooperative or competitive interaction can be assessed even when the individual is interacting with a computer program rather than another person. Transitions between the competitive and cooperative blocks were unsignaled, therefore subjects had to discover by trial and error the most successful strategy over consecutive blocks. This alternation between the two interaction modes functioned well because the participant's winning rate was significantly higher in cooperative (mean 60% std 1%) than in competitive (mean 44% std 1%) trials (paired t-test $p < 10^{-4}$).

516

517 **Artificial agent**

The AA calculated the probability p for the participant to select a particular target color based on the history of the two previous choices and their outcomes. Then to make the artificial agent behave more like a real person, this prediction was exploited in a probabilistic fashion (**see SI**). In the cooperative mode the AA chose the color card it predicted with probability p . In the competitive mode this color was chosen with probability $1-p$.

523

524 **Behavioral analysis**

For the logistic regressions, we reported significant marginal effect of a given variable under the name "*estimate*" (for example: *Cooperativity signature* t_{-1} : *estimate*).

Logistic regression : $\ln\left(\frac{P}{1-P}\right) = x_0 + x_1X_1 + x_2X_2 + \dots$

X_i represents independent variables and x_i represents the associated weights in the logistic regression. P represent the probability of a given event. The marginal effect of the variable X_1 is defined as:

$$\widehat{y}_1 = \text{mean}(\text{logit}^{-1}(x_1))$$

The mean is computed across all observed data. Thus, the marginal effect called “*estimate*” can easily be interpreted as the discrete change of the dependent variable given a unitary change of an independent variable.

For the linear regressions, reported “*estimate*” represents x_i i.e. the regression coefficient. Indeed, in a linear regression, marginal effect of a variable is equal to the estimated coefficient.

Models

To test for a dynamic tracking of implicit intention we compared 14 models, 9 involved theory of mind (*Inf,k-ToM*), the others were to control for other possible strategies. The influence models (*Inf*) rely on aaylor expanded reinforcement learning⁶² to take into account the influence of one’s own strategy on the strategy of the other. *k-ToM* models also take into account the influence of one’s own strategy on the other but in a Bayesian fashion^{13,35}. These two models were adapted in their cooperative and competitive versions. Moreover, we constructed an adaptation of these two models (*Inf,k-ToM*) in which an arbitrator weights the cooperative and competitive versions according to their reliability before making the decision. Finally, because *k-ToM* is a recursive model (“I think that you think that...”), we included *k-ToM* of depth one and two for each version.

To control for strategies that did not include theory of mind we added 5 other models including two Bayesian inference types (*HGF* and *BSL*). The Hierarchical Gaussian Filter (*HGF*)^{43,63} basically tracks the external volatility of the artificial agent choices in a Bayesian hierarchical way. The Bayesian Sequences Learner (*BSL*) strategy relies on Bayesian inference given past sequences of choices. In a model free analysis, we found that participants tended to use the past 2 choices to make their next choice, so we used sequences of depths 2 and 3. Finally, we added two non-Mentalizing non Bayesian models, a reinforcement learning model (RL) and a model based on the heuristic Win/stay – Lose/Switch that we observed in the model free analysis.

The Bayesian Model Selection (BMS) was performed using the VBA toolbox (Variational Bayesian Analysis) in a random effect analysis relying on the free energy as the lower bound of model evidence. We use protected Exceedance Probability measurements (pEP)⁴⁵ to select the model which is used most frequently in our population.

<i>Model</i>	<i>Mentalizing</i>	<i>Bayesian</i>	<i>Mixed intentions</i>
<i>Influence</i>	+	-	-
	(coop and comp)		
<i>Fictitious</i>	+	-	-
<i>Influence mixed intentions</i>	+	-	+
<i>k-ToM</i>	+	+	-
	(coop and comp)	(depth 1 and 2)	
<i>k-ToM mixed intentions</i>	+	+	+
<i>Active Inferences</i>	-	+	-
<i>HGF</i>	-	+	-
<i>BSL</i>	-	+	-
		(depth 2 and 3)	
<i>RL</i>	-	-	-
<i>Wst/Lsw</i>	-	-	-

Table 1. Classification of models according to 3 categories. The first depends on the ability of the model to mentalize, the second depends on whether the model is a Bayesian model, and the third concerns models that could be used with a mixture of experts.

fMRI data acquisition

MRI acquisitions were performed on a 3 Tesla scanner using EPI BOLD sequences and T1 sequences at high resolution. Scans were performed in a Siemens Magnetom Prisma scanner HealthCare at CERMEP Bron (single-shot EPI, TR / TE = 1600/30, flip angle 75°, multiband acquisition (accelerator factor of 2), in an ascending interleaved manner with slices interlaced 2.40 mm thickness,

571 FOV = 210 mm. We also use the iPAT mode with an accelerator factor of 2 and the GRAPPA method
572 reconstruction. The number of volumes acquired varied given the time the participant took to make their
573 decisions. The first acquisition was made after stabilization of the signal (3 TR). Whole-brain high-
574 resolution T1-weighted structural scans (0.8 x 0.8 x 0.8 mm) were acquired for each subject, co-
575 registered with their mean EPI images and averaged across subjects to permit anatomical localization
576 of functional activations at the group level. Field map scans were acquired to obtain magnetization
577 values that were used to correct for field inhomogeneity.

578

579 **fMRI data analysis**

580 Image analysis was performed using SPM12 (Wellcome Department of Imaging Neuroscience,
581 Institute of Neurology, London, UK, fil.ion.ucl.ac.uk/spm/software/spm12/). Time-series images were
582 registered in a 3D space to minimize any effect that could result from participant head-motion. Once
583 DICOMs were imported, functional scans were realigned to the first volume, corrected for slice timing
584 and unwarped to correct for geometric distortions. Inhomogeneous distortions-related correction maps
585 were created using the phase of non-EPI gradient echo images measured at two echo times (5.20 ms
586 for the first echo and 7.66 ms for the second). Finally, in order to perform group and individual
587 comparisons, they were co-registered with structural maps and spatially normalized into the standard
588 Montreal Neurological Institute (MNI) atlas space using the DARTEL method. Then we ran ARTrepair
589 to deweight scans that could include movement artefacts ⁶⁴.

590 We ran general linear models (GLMs) analyses to identify which brain regions encoded: (a)
591 one's belief that one is interacting in a cooperative or in a competitive situation (Δ); (b) the reward
592 prediction error (PE) after interactions classified as cooperative or competitive; (c) the PE difference
593 between the trials classified as cooperative vs competitive. In every GLM, an event was defined as a
594 stick function. The participant's button press and the AA's selection of target were defined as onset of
595 no interest in all GLMs. For all GLMs, missing trials were modeled with four events (cue, participant's
596 button press, AA's choice and outcome) as separate onsets without additional parametric regressors.
597 Head movement parameters were added as parametric regressors of no interest to account for motion-
598 related noise. Because the behavioral analysis showed that the bias towards competitive interaction
599 affects the strategy of participants, we added the competitive bias (δ) as a covariate at the second level
600 analysis in all GLMs.

601 Specifically, in GLM1, there were 4 onsets, including the time of the cue presentation (cards on
602 screen), participant's button press, AA's choice and the feedback time. Parametric regressors were the
603 difference in reliability Δ , the expected reward for staying at the time of the cue onset and the reward
604 prediction error (PE) at the feedback time, as well as Δ , to control for the effect of the believed intention

of the other on the PE brain encoding. For each GLM, we turned off the serial orthogonalization function of regressors to allow it to compete for the variance.

In a second GLM (GLM2), we separated trials given the sign of $\Delta - \delta$ (positive or negative) to identify brain regions specifically engaged in cooperative or competitive mental states (δ is a free parameter capturing the participant's bias toward competitive intent). Δ refers to the difference in reliability of cooperative and competitive prediction and δ is the competitive bias. For this GLM, there were 6 onsets, including the cue for trials classified as cooperative or competitive, participant's button press, AA's choice and the feedback time for trials classified as cooperative or competitive. Trials were classified as either cooperative or competitive and parametric modulators were: the difference in reliability Δ and the expected reward for staying on the same target at the time of the cue and the PE and Δ at the time of feedback. Three participants who always attributed the same intention to the AA were not included in GLM2.

To test the additional hypothesis that brain activation observed for believed other's intentions (in **Fig. 4b**) is also present in competitive vs cooperative blocks, we conducted two more GLMs. The first, GLM3 is similar to GLM2, i.e., we separated trials into two categories (cooperative and competitive), but the differentiation was made using the real mode of interaction of the AA rather than the classification made by the controller. Other onsets and parametric regressors were left unchanged.

Finally, a last GLM was applied to check that the results observed in GLM2 were not simply due to the effect of volatility of the rewarded target. This GLM (GLM4) is similar to GLM2, i.e. trials were classified according to the sign of $\Delta - \delta$. The only difference was that we added the actual probability that the AA would choose the same target as the previous trial as a parametric regressor at both the time of the cue and at the outcome.

We computed one sample t-tests with contrasts for main effect of Δ in GLM1 and effect of PE at the outcome time. Then we computed the contrast between competitive and cooperative PE regressors in GLM2, GLM3 and GLM4. Finally, we computed a paired t-test between this contrast, derived from GLM2 and GLM3, to formally show that activation coming from the difference between classified trials was significantly higher than those coming from the difference between the actual modes of interaction as determined by the trial block.

Reported brain areas show a significant activity at the threshold of $p < 0.05$, whole brain family-wise error (FWE), corrected for multiple comparisons at the cluster level (threshold at $P < 0.001$ uncorrected).

637 **Psychophysiological interaction (PPI) analysis**

638 We defined the attribution of cooperative or competitive intentions at the time of decision making
639 as the psychological factor. Thus, we were able to investigate the difference in functional connectivity
640 when making a decision under cooperative or competitive intent. For this PPI analysis, we focused on
641 decision time and on functional connectivity between regions encoding the others' intentions and all
642 other voxels. Thus, for the physiological factor we took the BOLD signal of the striatal region elicited in
643 GLM1 as encoding the intention of others. Otherwise, we used same regressor parameters and onsets
644 as GLM2.

645 Reported brain areas show a significant activity at the threshold of $p < 0.05$, whole brain family-
646 wise error (FWE) corrected for multiple comparisons at the cluster level (threshold at $P < 0.001$
647 uncorrected).

648

Figures

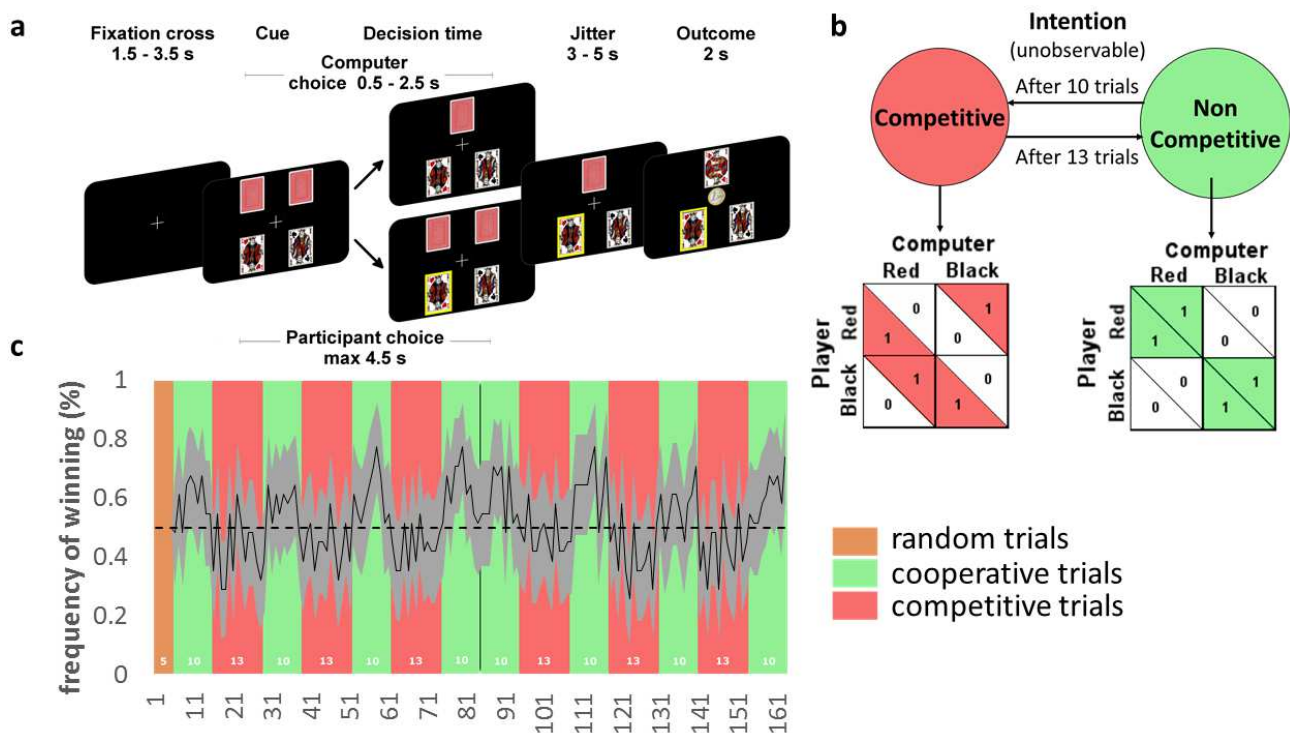
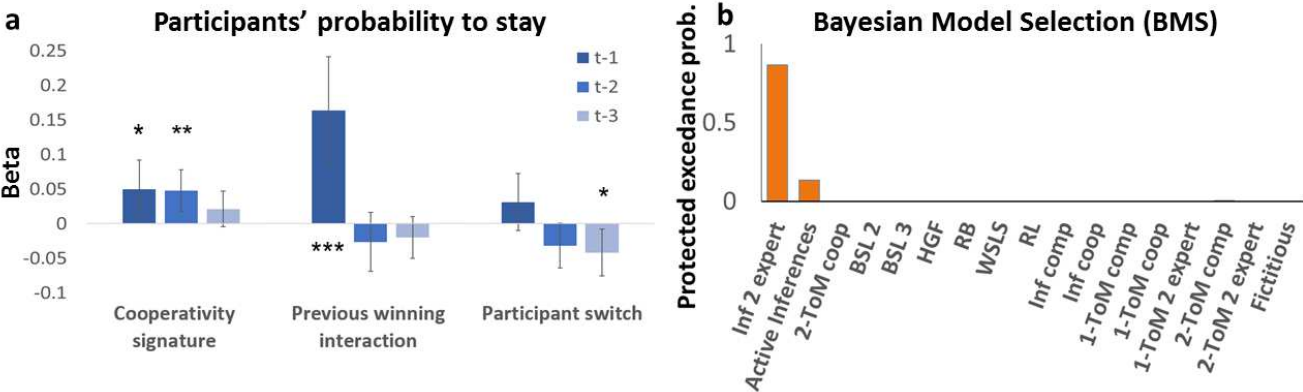


Figure 1. fMRI experiment. **a.** After a fixation cross, four cards were presented on the screen. The two cards shown on top of the screen represent the cards presented to the opponent/partner (i.e. Artificial agent), and not seen by the participant while the two kings (one black and one red) are the cards presented to the participant (shown in the bottom of the screen). The participants had to choose between these two cards. At the time of decision, the upper screen represents the display if the AA makes it choice first, while the lower screen shows how one card is highlighted with yellow border if the participant makes his choice first. Then a screen presents the participant's and Artificial Agent's choices together. Finally, at the time of outcome the participant wins if both he/she chooses the same card as the AA (here red king). **b.** Payoff matrix of the two types of block. **c.** Frequency of winning (black line) during competitive (red background) and cooperative (green background) blocks. The grey area represents the 95% confidence interval. The orange background represents 5 initial trials in which the AA played randomly for initialization purpose.



667 **Figure 2. a.** Model-free analysis. Random-effect logistic regression of the decision to stay after
668 selecting a specific target with respect to the action of the artificial agent “Cooperativity signature” (i.e.
669 participant wins then AA stays or participant loses then AA switches), the previous winning interaction
670 (i.e. success or failure of past trials) and the choice to switch or stay, over the previous three trials. Error
671 bars are the 95% confidence interval. **b.** Model comparisons based on Bayesian model selection. The
672 protected exceedance probabilities indicate that the Mixed-Intention Influence model (Inf 2 expert)
673 explains decisions in the mixed intention task better than others: Active inference; k-ToM; Bayesian
674 Sequence Learner (BSL); Hierarchical Gaussian Filter (HGF); Reinforcement Learning (RL); Heuristic
675 models: Random Bias (RB); Win/Stay-Lose/Switch (WSLS).

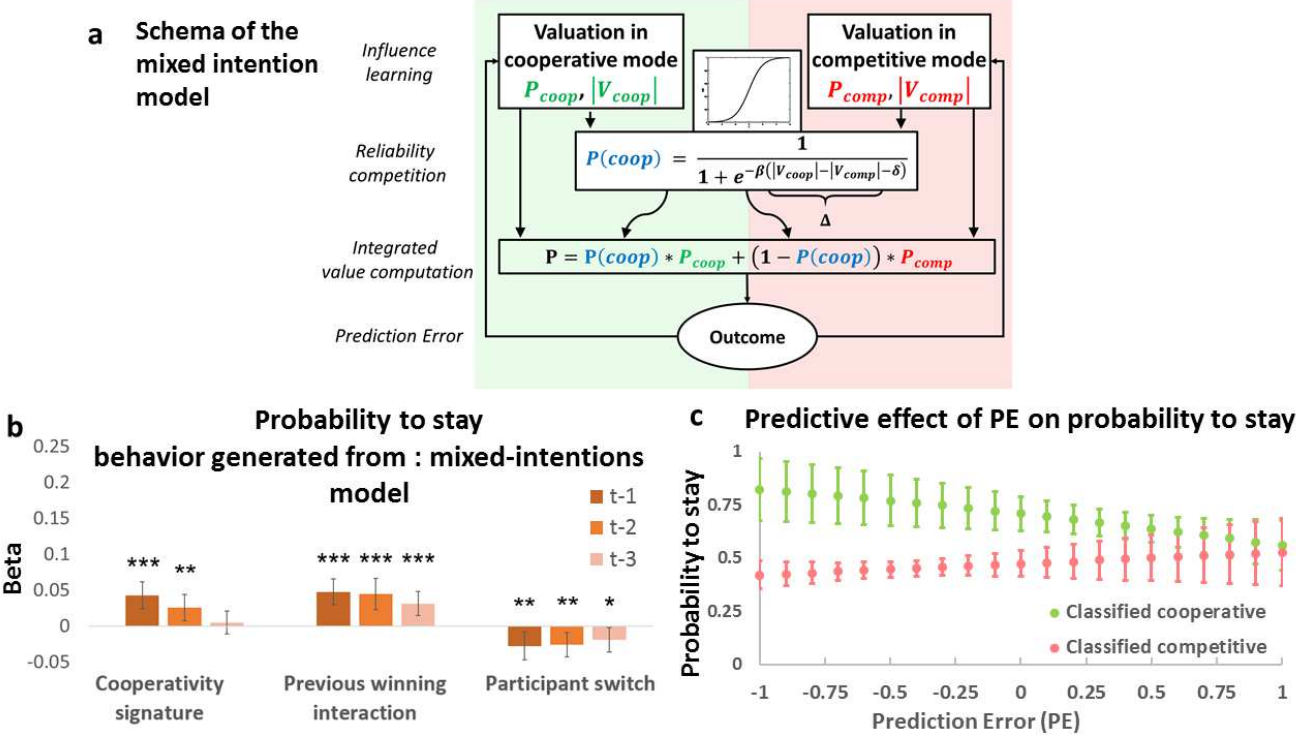


Figure 3. a. Scheme of the Mixed-Intention Influence model. Two influence models (one cooperative and the other competitive) compute a value for choosing one specific target (the black one). A controller uses the difference between the absolute value of the value of each expert (called reliability) to compute a probability that the other is cooperating. Then, the model weights the value of each expert according to the probability of being in cooperative and in competitive modes to produce a final decision value. Then it compares its predictions to the actual reward and compute again a new value for each expert. **b.** Model-free generative analysis. We generated one hundred sets of data using a free parameter from a normal distribution with mean and standard deviation calculated from the models fitted to the population, against the same artificial agent that participants played. We regressed the behavioral decision to stay after selection of a specific target on the previous trial depending on the interaction of the previous outcome and the action of the artificial agent (“Cooperativity signature”), the success or failure of up to three previous trials, and the action to switch or stay of the participant. Error bars are the 95% confidence interval (random-effect logistic regression). **c.** Marginal effect of the prediction error on the probability to stay on the same target in trials classified as Cooperative (green) and trials classified as Competitive (red). Error bars are the 95% confidence interval. *p < 0.05, **p < 0.01, ***p < 0.001 (random-effect logistic regression).

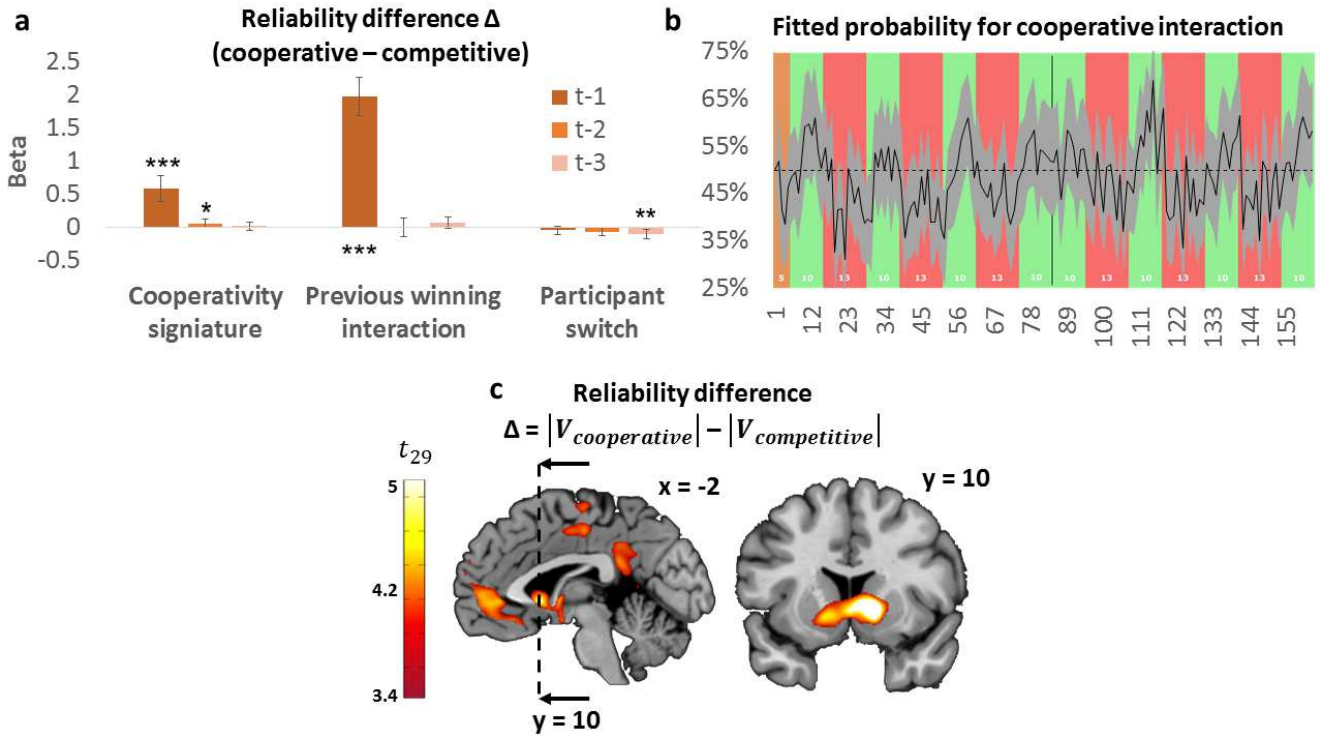


Figure 4. a. Difference in reliability is influenced by the Cooperativity signature of the Artificial Agent (AA), specifically the interaction of the previous subject's outcome followed by the action of the artificial agent (Participant wins then AA stays and Participant loses then AA switches), the latest outcome and the computer's switch at trial t-2 and t-3. Error bars are the 95% confidence interval. **b.** Mean probability of the participant attempting to cooperate across all participants (black line) for the 163 trials. The initial orange area is the 5 random initializing trials, green areas are the Cooperative blocks and red areas the Competitive blocks. The grey area is the 95% confidence interval. **c.** BOLD signal in ventral striatum, mPFC and posterior cingulate cortex (PCC) ($p < 0.05$ whole-brain family-wise error) are correlated with the difference in reliability, Δ , of estimated competitive and cooperative intentions.

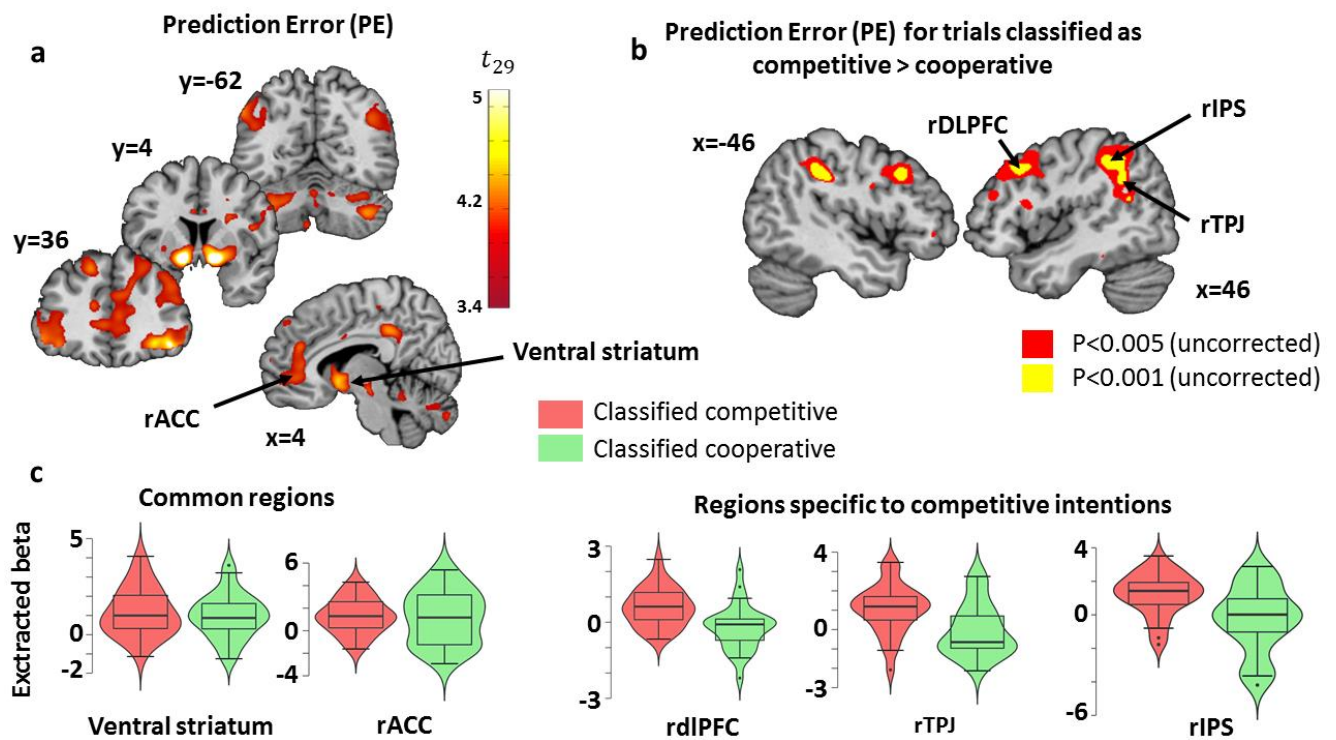
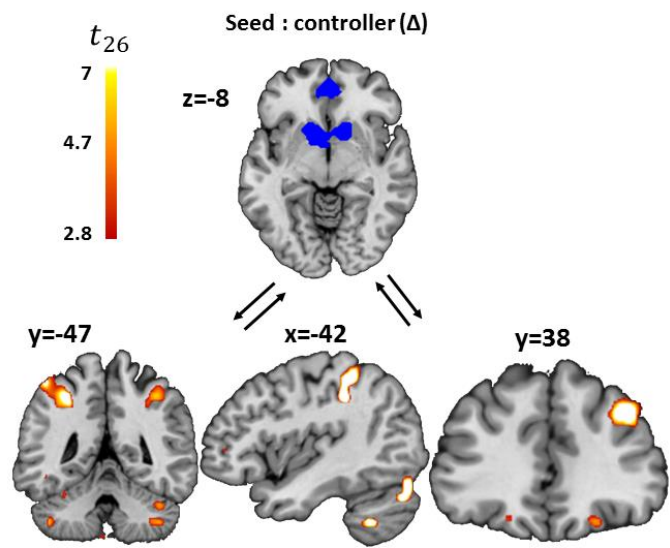


Figure 5. Correlations between BOLD activity and prediction error. **a.** Brain regions in which BOLD signal correlates with prediction errors for trials classified by the controller to be either competitive or cooperative. **b.** Brain regions in which BOLD activity correlates more with PE on trials estimated to be competitive compared to trials estimated to be cooperative. This network comprised dlPFC ($x,y,z = 30,9,42$), IPS ($x,y,z = 42,-47,42$) and the rTPJ ($x,y,z = 51,-50,33$, $p < 0.05$ whole-brain family-wise error). **c.** Beta value extracted for trials estimated to be either competitive or cooperative. Left: regions in the ventral striatum (left $x,y,z = -14,3,-11$ + right $x,y,z = 17,6,-12$) and rACC ($x,y,z = 6,42,-3$) with increased activation in trials estimated to be either competitive or cooperative. Right: specific brain regions activated only when trials were classified as Competitive: dlPFC ($x,y,z = 30,9,42$), IPS ($x,y,z = 42,-47,42$) and rTPJ ($x,y,z = 51,-50,33$) from 8 mm spheres centered on peak activation.



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Figure 6. Neural mechanisms of arbitration between the attributions of competitive and cooperative intentions to the AA. Connectivity analysis: the BOLD signal was extracted from seeds regions (mPFC and ventral striatum using GLM1) computing the reliability difference between cooperative and competitive intentions of others (in Blue). The psychophysiological interaction effect shows higher functional coupling (voxels in red) with the left TPJ ($x, y, z = -42, -40, 50$), left IPS ($x, y, z = -32, -48, 50$) and right dlPFC ($x, y, z = 38, 34, 34$, $p < 0.05$ FWE threshold at $p < 0.001$) in trials classified as competitive as compared to those classified as cooperative.

729 **Extended data**

730 **Extended table**

731

732 Extended results table of GLM1, related to **Figure 4c**.

Table 1. Brain region that covaries with difference in reliability of interaction mode

	MNI peak cluster coordinates			k	Z score
	x	y	z		
Difference in reliability (Δ=Rcoop -Rcomp)					
Ventral Striatum	14	9	-2	3375	4,99
Left hippocampus	-35	-53	3	660	4,3
mPFC	6	45	-8	1580	4,24
Right hippocampus	32	-36	12	3836	4,11
Middle cingulate cortex	11	-15	57	1732	3,95
Left Angular	-32	-53	27	857	3,86
Left postcentral gyrus	-20	-44	48	661	3,85
Rcomp – Rcoop					
No brain region					

** cluster reported at $p < 0.05$ FWE whole brain cluster corrected (initial cluster-forming threshold of $p < 0.001$ uncorrected)

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735 Extended results table of GLM2, related to **Figure 5a**.

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Table 2. Brain region encoding both competitive and cooperative prediction error.

	MNI peak cluster coordinates			k	Z score
	x	y	z		
Positively					
Right Dorsal Striatum	17	6	-12	21895	8,79
Left Dorsal Striatum	-14	3	-11	3488	8,78
Left Cerebellum	-44	-74	-45	6381	5,49
Right Cerebellum	29	-71	-29	5299	5,33
PCC	2	-35	38	1285	5,3
Right Angular/TPJ	45	-30	47	3581	4,71
Left Angular/TPJ	-54	-62	39	2044	4,34
Negatively					
No brain region					

** cluster reported at $p < 0.05$ FWE whole brain cluster corrected (initial cluster-forming threshold of $p < 0.001$ uncorrected)

737

738

739 Extended results table of GLM2, related to **Figure 5c**.

Table 3. Brain region that responded differently for the reward prediction error of a trial estimated to be competitive rather than cooperative

	MNI peak cluster coordinates			k	Z score
	x	y	z		
Competitive > Cooperative					
Right dlPFC	35	11	36	1732	4,41
		-			
Right Angular/TPJ	50	50	32	1758	4,32
Medial superior frontal gyrus	-2	30	47	505	3,82
Cooperative > Competitive					
No brain region					

** cluster reported at p<0.05 FWE whole brain cluster corrected (initial cluster-forming threshold of p<0.001 uncorrected)

740

741 Extended results table of connectivity analysis, related to **Figure 6**.

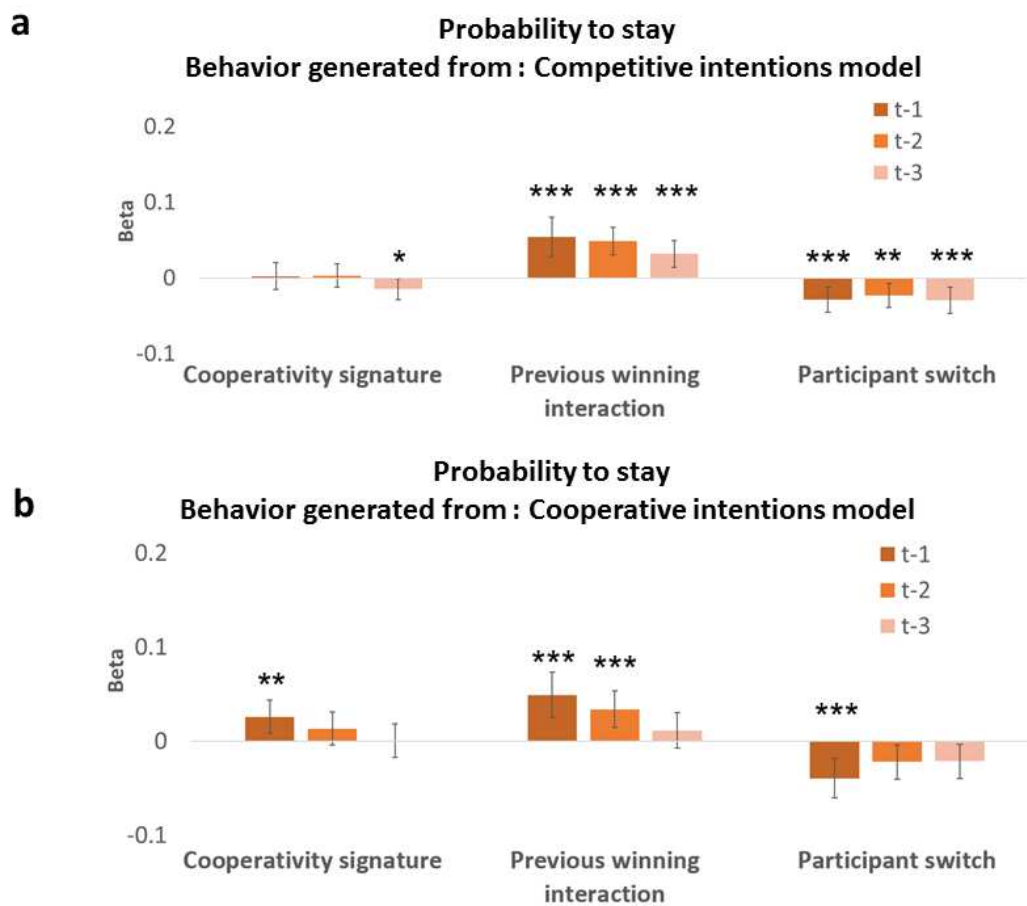
Table 4. Effect of the intention attribution at the decision time on the striatum/mPFC and dIPFC/TPJ connectivity strength.

gPPI Analyse	Seed	Peak regions	k	p-val unc.	p-val FWE	Z score
Competitive > Cooperative	<i>mPFC + striatum</i>	-48 -44 58	363	<0.0005	<0.0005	4.52
	<i>mPFC + striatum</i>	-2 -82 -36	153	<0.0005	0.037	4.34
	<i>mPFC + striatum</i>	38 34 34	150	<0.0005	0.040	4.33
	<i>mPFC + striatum</i>	-38 -78 -26	181	<0.0005	0.017	4.27
	<i>mPFC + striatum</i>	4 -46 16	744	<0.0005	<0.0005	4.48
Cooperative > Competitive	<i>mPFC + striatum</i>	4 -46 16	744	<0.0005	<0.0005	4.48

742

743 **Extended figures**

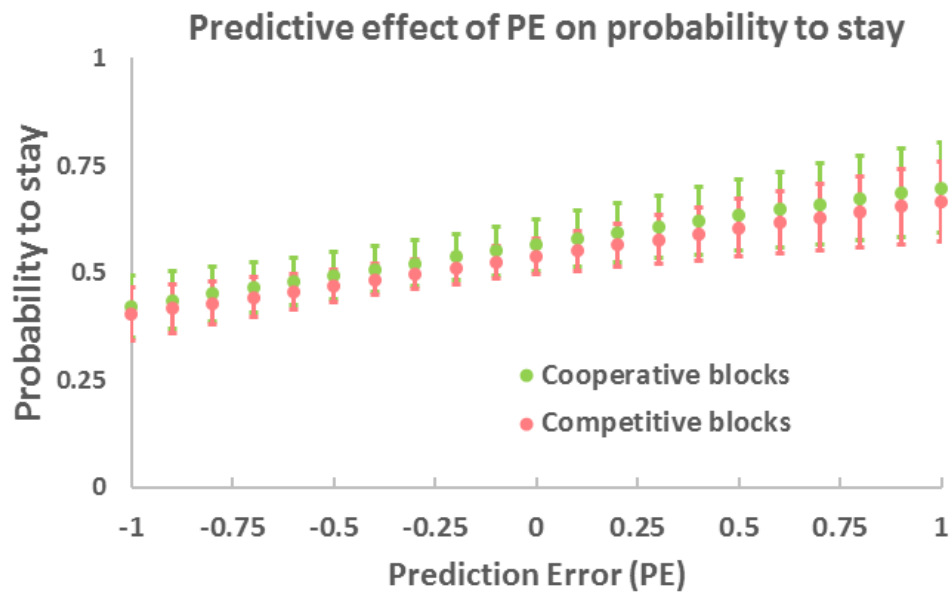
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746 **Extended figure 1.** Model-based generative analysis. We generated one hundred sets of data using
747 free parameters from a normal distribution with mean and standard deviation calculated from the
748 "Influence models" in competitive (a) and cooperative (b) mode, fitted to the population. We generated
749 a data set against the same artificial agent that participants played. We regressed the interaction of the
750 previous outcome and action of the artificial agent (I win – AA stay / I lose – AA switch), the behavioral
751 decision to stay after selecting a specific target at the previous trial based on the success or failure of
752 the previous trial (Win) and the action to switch or stay of the artificial agent (Switch) in previous trials
753 up to three trials back. Error bars are the 95% confidence interval. *p < 0.05, **p < 0.01, ***p < 0.001
754 (random-effect logistic regression). Related to Computational models tracking intentions of the other
755 agent in the Result part.

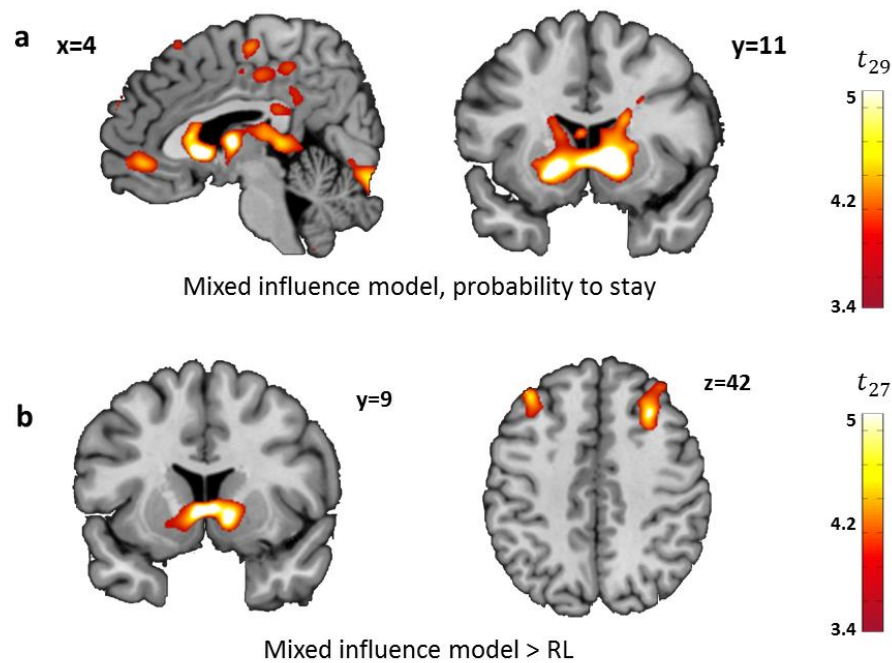
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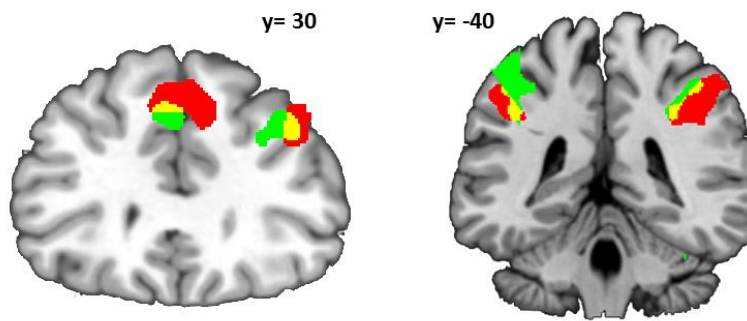
758 **Extended figure 2.** Marginal effect of the prediction error on the probability to stay on the same target
 759 in Cooperative blocks (green) and in Competitive blocks (red). Error bars are the 95% confidence
 760 interval. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (random-effect logistic regression). Related to Computational
 761 models tracking intentions of the other agent in the Result part.

762



763
 764 **Extended figure 3.a.** Neural correlates of the expected reward for staying on the same target as the
 765 previous trial, computed by the Mixed-Intention Influence model. (Significant ventral striatum correlation
 766 $x,y,z=14,11,-2$, $p<0.05$ FWE corrected threshold at $p<0.001$) **b.** Ventral Striatum ($x,y,z=6,12,0$), bilateral
 767 dlPFC ($x,y,z=-36, 33, 44$ and $x,y,z= 30,24,42$) and MTG ($x,y,z=65,-56,-8$, $p<0.05$ FWE corrected
 768 threshold at $p<0.001$) are best explained by the expected reward for staying of the Mixed-Intention
 769 Influence model rather than the expected reward for staying of a reinforcement learning model. Related
 770 to Model-based analyses in the result part.

771



772
773 **Extended figure 4.** Overlap (in yellow) of brain regions correlating more with PE when trials are
774 classified as competitive compared to those classified as cooperative (GLM2, in red), and of brain
775 regions more coupled with the controller region at the time of choice of trials classified as Competitive
776 compared to those classified as Cooperative (in green) ($p < 0.005$ for display purpose)
777

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