

An amygdala-mediated simulation-to-decision cascade aligns interbrain dynamics to solve social dilemmas

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Supplementary Notes

Supplementary Note 1: Permutation-based control analyses of IBRA.

To validate the observed increases in IBRA, we performed a series of permutation tests (Fig. 2d-j) on the time windows exhibiting significant IBRA increases for the amygdala (early and late IBRA increases in MC trials) and TPJ (IBRA increases in both MC and non-MC conditions; Extended Data Fig. 1). i) *Full-trial permutation*: For each channel-pair, each channel's 30 trials were shuffled and randomly paired with trials from the other channel to generate pseudo-MC trials (and pseudo-non-MC trials for TPJ). ii) *Paired-choice permutation*: For each channel-pair, the choices of the two participants were randomly paired to ensure outcomes as MC (i.e., C-C pairs) or non-MC (i.e., C-D or D-D pairs) to generate pseudo-MC or pseudo-non-MC trials. iii) *Paired-outcome permutation*: Here, we shuffled trials where dyads achieved mutual cooperation (or failed to do so) to create pseudo-MC (or pseudo-non-MC) trials. For all three permutation methods, the trial count for pseudo-MC and pseudo-non-MC trials was kept consistent with that of the actual conditions. IBRA was recalculated for each channel-pair in the pseudo-trials, and this process was repeated 10,000 times to generate permutation distributions. The observed IBRA values were then compared against the 95% *CI* of these permutation distributions. The *p* values were calculated as $(b+1)/(m+1)$, where *b* is the number of permutation samples whose absolute value were greater than or equal to the observed one, and *m* is the total number of permutations⁷⁵. For the TPJ, all three permutation tests revealed that the observed IBRA values in both MC (Extended Data Fig. 1a-c) and non-MC (Extended Data Fig. 1d-f) conditions exceeded the 95% *CI* of the permutation distribution, indicating that TPJ IBRA is not condition-specific and sensitive to real-time interactions.

To validate amygdala IBRA in pMC dyads, we conducted a full-trial permutation test, since all decisions in pMC dyads were *cooperate* and the outcome was always MC. Specifically, for each channel-pair, we shuffled the 30 MC trials for each channel, generating pseudo-MC trials by random pairing. The IBRA for pseudo-MC was recalculated, and this process was repeated 10,000 times to construct a null distribution. Observed IBRA values from

pMC dyads were then compared to the permutation distribution to assess statistical significance.

Supplementary Note 2: Time-lagged IBRA analysis.

To examine the temporal precision and directionality of IBRA, we conducted time-lagged analysis. Rather than calculating correlations between feature vectors from paired channels within corresponding time windows ($\text{Rho}_{t,t}$, t representing time window t), we calculated the correlation between feature vectors of one channel across all time windows and those of another channel for each channel-pair ($\text{Rho}_{i,j}$, i/j representing time window for each channel, respectively). This generated a 1500ms×1500ms alignment map, with diagonal points representing time-locked IBRA (reported in the main text), and off-diagonal points representing time-lagged IBRA (Extended Data Fig. 7a). To assess general temporal diffusion, for each dyad, we randomly assigned one individual as sub1 (2) and the other as sub2 (1), organizing channels from sub1 (2) and sub2 (1) as dimensions 1 (2) and 2 (1) in the IBRA map. We then compared IBRA maps between MC and non-MC conditions across all channel-pairs using paired-sample t-tests with cluster-based permutation testing ($n = 5,000$). Moreover, we also conducted control analyses and confirmed that the diffuse pattern is not driven by the use of sliding windows or temporal smoothing when calculating IBRA (Extended Data Fig. 7f-i). The diffuse structure was significantly more pronounced during mutual cooperation than non-cooperation, indicating that it is functionally specific rather than a generic property of inter-brain coupling (Extended Data Fig. 7j-m).

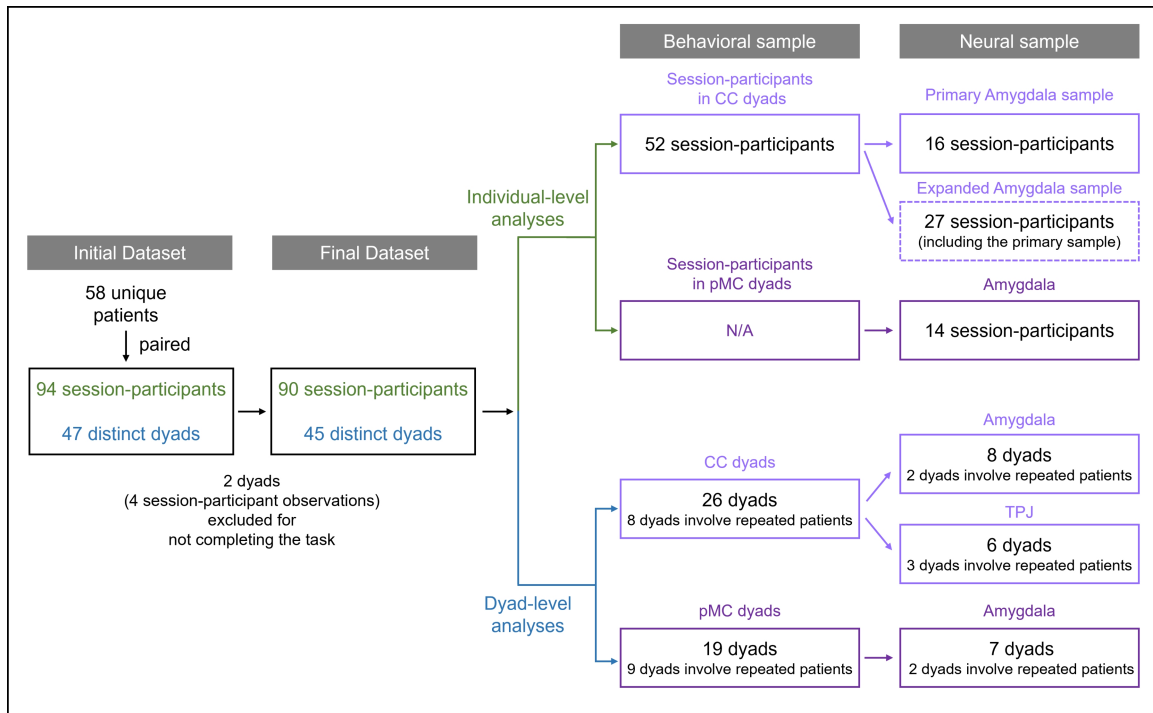
To test for behaviorally grounded directionality, we reconstructed asymmetric time-lagged IBRA maps using two metrics: social prediction strength and decision speed. For each dyad and each condition (MC, non-MC), we identified a “leader” (y-axis) based on two behavioral criteria: (i) social prediction strength (participant level): the participant who can more strongly predicted the partner’s choices by their own low-frequency power (derived from logistic regression models in Fig. 4c); (ii) decision speed (at the trial level): the participant with a faster decision time on a given trial. We then computed an asymmetry index^{76,77} (AI) by comparing IBRA values in the upper and lower triangles of the time-

lagged map (Extended Data Fig. 8). A positive AI indicates that the designated leader's neural patterns precede the other's. Statistical significance was assessed using Wilcoxon signed-rank tests across channel-pairs.

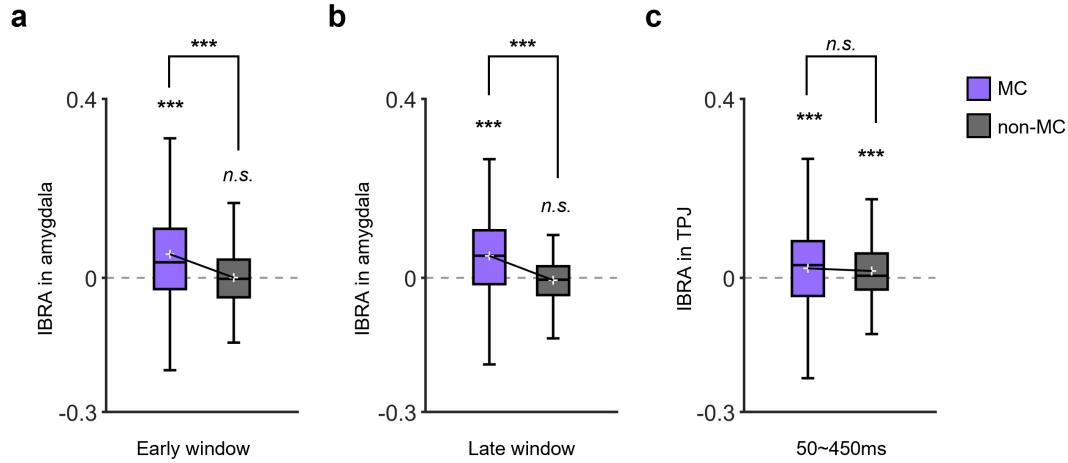
Supplementary Note 3: Cluster-based permutation test.

Cluster-based permutation tests were used to correct for multiple comparisons in all contrasts involving temporal or spectral clusters. Clusters were first identified as contiguous data points showing significant differences between conditions. Within each cluster, t -values were summed across all data points. In each permutation, we randomly shuffled the condition labels for each data point, calculated the condition difference, and extracted the largest summed t -value from all clusters. This procedure was repeated 10,000 (5,000) times to generate a permutation distribution. The cluster-level t -values in observed data were then compared against the 95% CI of the permutation distribution. The corrected p values were calculated as $(b+1)/(m+1)$, where b is the number of permutation samples whose absolute value was greater than or equal to the observed one for two-sided tests (b is the number of permutation samples whose value was greater (less) than or equal to the observed one for one-sided tests), and m is the total number of permutations⁷⁵.

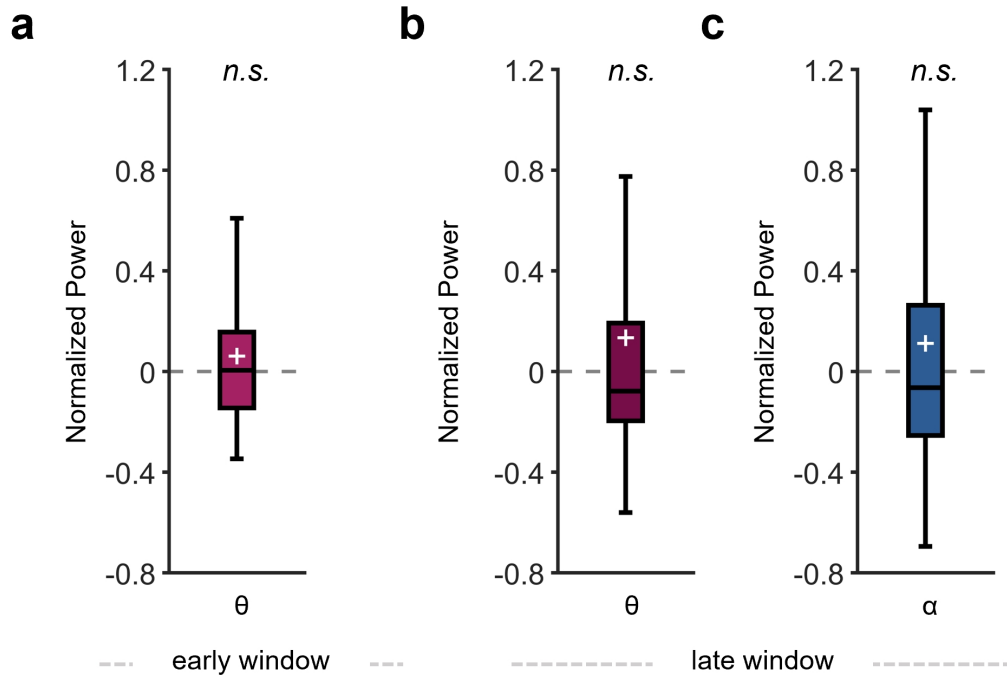
Supplementary Figures



Supplementary Fig. 1: Participant and analysis-sample flow. Fifty-eight unique patients contributed to 47 dyadic experimental sessions, corresponding to 94 session-participant observations. Two dyads (four session-participant observations) were excluded because they did not complete the task, leaving a final dataset of 45 distinct dyads, comprising 90 session-participant observations. Analysis samples are shown separately according to the unit of analysis. At the individual level, behavioral analyses in conditional-cooperator (CC) dyads included 52 session-participant observations; region-specific neural samples are shown for the primary and expanded amygdala analyses. Individual-level behavioral analyses were not applicable to pure-mutual-cooperator (pMC) dyads, whereas 14 session-participant observations contributed to the corresponding amygdala neural analysis. At the dyad level, behavioral analyses included 26 CC dyads and 19 pMC dyads. Region-specific neural analyses included 8 CC dyads for the amygdala, 6 CC dyads for the TPJ and 7 pMC dyads for the amygdala. Numbers of dyads involving repeatedly participating patients are indicated within the corresponding analysis boxes.

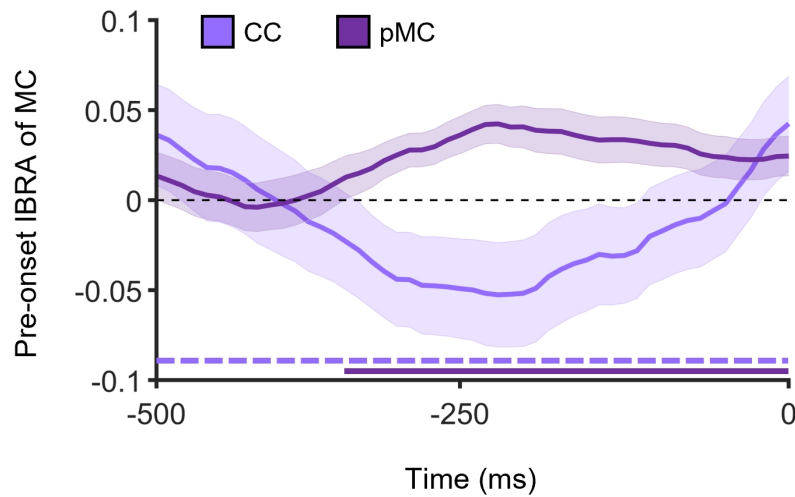


Supplementary Fig.2: Replication of inter-brain representational alignment (IBRA) results using a 100-ms sliding window. a-c, Time-averaged IBRA in amygdala (**a, b**) and TPJ (**c**) during mutual cooperation (MC, purple) and non-MC (grey) conditions. **a,b,** MC-specific increases in amygdala IBRA were robustly replicated in both the early (**a**, MC > non-MC, $t_{140} = 4.526$, $p = 1.27 \times 10^{-5}$, 95% CI: 0.030, 0.075, two-sided paired t-test; MC > zero, $t_{140} = 5.102$, $p = 5.37 \times 10^{-7}$, 95% CI: 0.036, Inf; non-MC > zero, $t_{140} = 0.090$, $p = 0.464$, 95% CI: -0.008, Inf, one-sided one-sample t-tests) and late (**b**, MC > non-MC, $t_{140} = 6.747$, $p = 3.68 \times 10^{-10}$, 95% CI: 0.038, 0.070; MC > zero, $t_{140} = 6.558$, $p = 4.87 \times 10^{-10}$, 95% CI: 0.037, Inf; non-MC > zero, $t_{140} = -1.364$, $p = 0.913$, 95% CI: -0.012, Inf) time window. **c,** In TPJ, IBRA increases were replicated for both MC and non-MC trials within the standardized 50-450ms window, derived from the empirically identified 90-410ms cluster: MC > zero, $t_{331} = 3.709$, $p = 1.22 \times 10^{-4}$, 95% CI: 0.012, Inf; non-MC > zero, $t_{331} = 4.401$, $p = 7.29 \times 10^{-6}$, 95% CI: 0.010, Inf; MC > non-MC, $t_{331} = 0.836$, $p = 0.404$, 95% CI: -0.008, 0.020. For consistency with the window-averaged analyses, the empirically identified 90-410 ms TPJ cluster was standardized to the adjacent 50-ms-aligned window of 50-450 ms. Box plots show medians (center line), interquartile ranges (box edges), whiskers (1.5×IQR), and mean values (crosses); black lines connect mean values across all channel pairs in each condition. *** $p < 0.001$, *n.s.*, not significant.



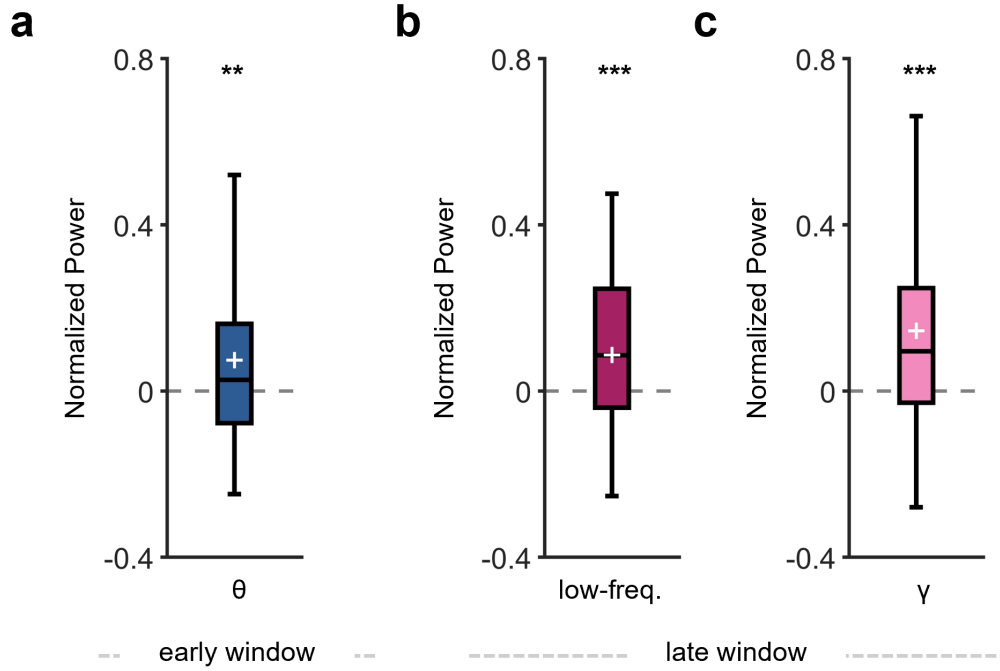
Supplementary Fig. 3: Suppressed low-frequency power was absent during unilateral cooperation.

Mean spectral power in the early theta (a), late theta (b), and late alpha (c) during unilateral cooperation. No significant suppression of low-frequency power was observed: early theta: $t_{56} = 1.194$, $p = 0.238$, $p_{corr} = 0.320$, 95% CI: -0.076, 0.300 (a), late theta: $t_{56} = 1.003$, $p = 0.320$, $p_{corr} = 0.320$, 95% CI: -0.134, 0.402 (b), late alpha: $t_{56} = 1.193$, $p = 0.238$, $p_{corr} = 0.320$, 95% CI: -0.042, 0.165 (c). Box plots show medians (center line), interquartile ranges (box edges), whiskers (1.5×IQR), and mean values (crosses). P values were assessed through two-sided one-sample t-tests with FDR correction for multiple comparisons. *n.s.*, not significant.



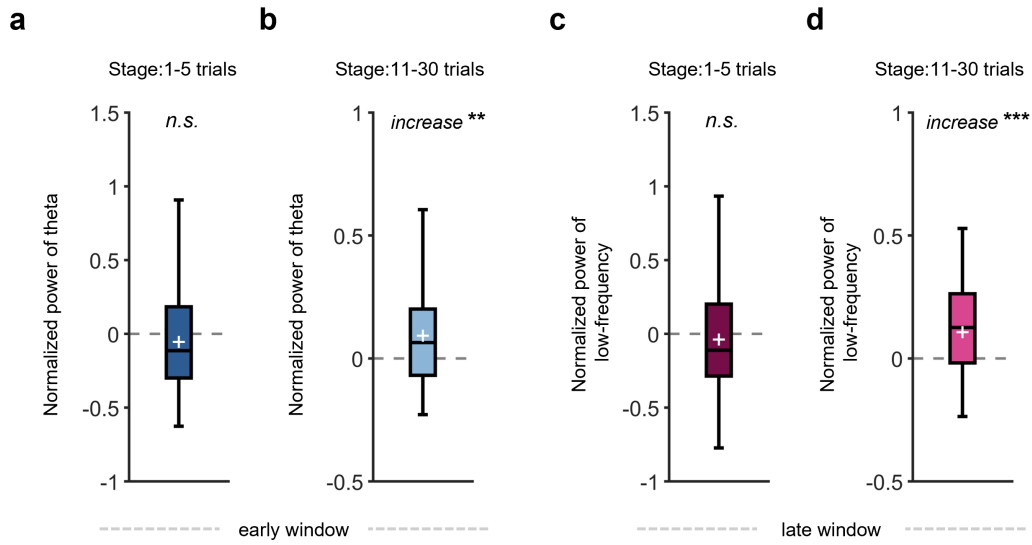
Supplementary Fig. 4: Pre-onset IBRA of MC in conditional cooperator (CC) and pure mutual cooperator (pMC) dyads.

Time courses of pre-onset IBRA of MC, from -500ms to onset in CC (light purple) and pMC (dark purple) dyads. Colored curves represent mean values across channel-pairs with shaded areas indicating 95% CIs. A significant IBRA cluster was observed in pMC dyads from -340 ms to 0 ms (horizontal solid line, one-sided one-sample t-test, cluster-based permutation test, $n = 10,000$), whereas no significant pre-onset IBRA was found in CC dyads (horizontal dashed line).



Supplementary Fig. 5: Spectral patterns of early and late amygdala IBRA in pMC dyads.

Power amplitude averaged within early theta (a), late low-frequency (b), and late gamma (c) time-frequency windows in the amygdala of pMC dyads. a, Early theta power showed significant increases ($t_{61} = 2.779$, $p = 0.007$, $p_{corr} = 0.007$, 95% CI: 0.021, 0.128). b,c, Late low-frequency and gamma power showed significant increases: late low-frequency, $t_{61} = 3.482$, $p = 9.26 \times 10^{-4}$, $p_{corr} = 0.001$, 95% CI: 0.037, 0.136 (b); late gamma, $t_{61} = 4.297$, $p = 6.33 \times 10^{-5}$, $p_{corr} = 1.90 \times 10^{-4}$, 95% CI: 0.078, 0.212 (c). Box plots show medians (center lines), interquartile ranges (box edges), whiskers (1.5×IQR), and mean values (crosses). Late low-freq. was defined as the mean power of theta-alpha band within late time window (300-650ms). P values were assessed through two-sided one-sample t-tests with FDR correction for multiple comparisons. *** $p < 0.001$, ** $p < 0.01$.



Supplementary Fig. 6: pMC dyad show no low-frequency power increase during the early stage of interaction.

Mean spectral power of early theta (**a,b**) and late low-frequency (**c,d**) in pMC dyads during two interaction stages (trials 1-5 vs. trials 11-30). **a,b**, Significant theta power increases were observed only in the later stage (**a**: trials 1-5, $t_{61} = -1.207$, $p = 0.232$, $p_{corr} = 0.309$, 95% *CI*: -0.146, 0.036; **b**: trials 11-30, $t_{61} = 3.244$, $p = 0.002$, $p_{corr} = 0.004$, 95% *CI*: 0.036, 0.150, two-sided one-sample t-tests). **c,d**, Significant low-frequency power increases were also observed only in the later stage (**c**: trials 1-5, $t_{61} = -0.831$, $p = 0.409$, $p_{corr} = 0.409$, 95% *CI*: -0.121, 0.050; **d**: trials 11-30, $t_{61} = 4.386$, $p = 4.65 \times 10^{-5}$, $p_{corr} = 1.86 \times 10^{-4}$, 95% *CI*: 0.058, 0.156). Box plots show medians (center lines), interquartile ranges (box edges), whiskers ($1.5 \times \text{IQR}$), and mean values (crosses). *P* values were assessed through two-sided one-sample t-tests with FDR correction for multiple comparisons. *** $p < 0.001$, ** $p < 0.01$, *n.s.*, not significant.

Supplementary Tables

Supplementary Table 1. Demographic and electrode information of 45 dyads. Dyad age was reported as the mean age of the two patients within each dyad. The number of clean channels per dyad was calculated as the sum of channels from both patients. M: male, F: female.

a. Conditional-cooperator dyads ($n = 26$)

Dyad ID	Age	Gender	Number of clean channel-pairs		Number of clean channels	
			Amygdala	TPJ	Amygdala	TPJ
D01	32	F-M	N/A	66	6	17
D02	24	F-M	24	48	11	14
D03	17	F-M	15	N/A	8	8
D04	25	F-M	N/A	N/A	7	12
D05	25	M-M	72	N/A	17	6
D06	30	F-M	N/A	N/A	3	5
D07	36	F-M	N/A	N/A	1	9
D08	16	F-M	N/A	N/A	N/A	7
D09	15	M-M	4	N/A	4	N/A
D10	22	M-M	N/A	N/A	5	10
D11	17	F-F	N/A	N/A	3	2
D12	10	F-F	N/A	N/A	1	1
D13	28	M-M	6	N/A	5	1
D14	21	F-M	N/A	N/A	3	N/A
D15	21	M-M	N/A	N/A	4	8
D16	21	F-F	N/A	N/A	N/A	3
D17	21	F-F	N/A	N/A	N/A	6
D18	22	M-M	N/A	119	N/A	24
D19	20	M-M	N/A	28	N/A	11
D20	30	F-M	N/A	35	6	12
D21	24	F-M	N/A	N/A	1	4
D22	14	M-M	N/A	N/A	N/A	32
D23	26	F-M	N/A	36	N/A	12
D24	30	M-M	6	N/A	5	5
D25	25	M-M	9	N/A	6	N/A
D26	37	M-M	5	N/A	6	N/A
Total (CC)	-	-	141 (8 dyads)	332 (6 dyads)	102	209

b. Pure-mutual-cooperator dyads ($n = 19$)

Dyad ID	Age	Gender	Number of clean channel-pairs		Number of clean channels	
			Amygdala	TPJ	Amygdala	TPJ
D27	36	F-M	8	20	6	12
D28	37	F-M	12	N/A	7	2
D29	31	F-F	N/A	N/A	1	5
D30	23	F-M	N/A	N/A	5	6
D31	31	F-M	N/A	N/A	7	2
D32	36	F-M	7	10	8	7
D33	28	M-M	35	12	12	8
D34	22	M-M	N/A	68	N/A	21
D35	32	F-M	N/A	80	6	21
D36	36	F-M	48	12	14	7
D37	22	F-M	N/A	128	2	36
D38	28	M-M	N/A	N/A	8	3
D39	26	M-M	N/A	96	8	35
D40	18	F-M	21	N/A	10	N/A
D41	25	M-M	N/A	N/A	1	6
D42	35	M-M	N/A	N/A	N/A	9
D43	26	M-M	N/A	N/A	3	6
D44	26	M-M	N/A	54	3	15
D45	26	M-M	6	N/A	5	N/A
Total (pMC)	-	-	137 (7 dyads)	480 (9 dyads)	106	201
Total (all)	-	-	278 (15 dyads)	812 (15 dyads)	208	410

Supplementary Table 2. Full statistical reports for behavior analyses. LME: Linear mixed-effect model. GLME: Generalized LME model.

Figure	Sample size	Statistical test	Test statistics and <i>p</i> values
Fig. 1e	<i>n</i> = 780, trials across all dyads	LME (M1, M2)	$t_{778} = -3.604, p = 3.33 \times 10^{-4}, 95\% \text{ CI: } -0.394, -0.116$
Fig. 1f			$t_{778} = 2.320, p = 0.021, 95\% \text{ CI: } 0.028, 0.338$
Fig. 1g	<i>n</i> = 754, trials (2-30) across all dyads	GLME (M3)	$t_{752} = 7.378, p = 4.27 \times 10^{-13}, 95\% \text{ CI: } 0.621, 1.072$
Fig. 1h	<i>n</i> = 397, MC trials (2-30) across all dyads	LME (M4)	$t_{395} = -3.300, p = 0.001, 95\% \text{ CI: } -0.317, -0.080$

M1: $dDT \sim MC + (1|dyad) + (1|dyad: trial)$, *dDT*: dyad mean decision time, MC is coded 1=MC, 0=non-MC;

M2: $dDTsim \sim MC + (1|dyad) + (1|dyad: trial)$, *dDTsim*: dyadic decision time similarity;

M3: $MC \sim MC_rate_3 + (1|dyad) + (1|dyad: trial)$, *MC_rate_3* is proportion of past 3 trials that ended with MC;

M4: $dDT_MC \sim MC_rate_k + (1|dyad) + (1|dyad: trial)$, *k*=3.

Supplementary Table 3. Statistics of history-length analyses. GLME: Generalized LME model.

a. Statistics of prediction models from three history measures.

Regressor	Statistical test	Standardized coefficients (β) and p values				
		$k = 1$	$k = 2$	$k = 3$	$k = 4$	$k = 5$
<i>MC_rate_k</i>	GLME (M3)	$\beta=0.428$ $p=8.41 \times 10^{-6}$ $p_{corr}=2.10 \times 10^{-5}$	$\beta=0.712$ $p=9.62 \times 10^{-11}$ $p_{corr}=3.61 \times 10^{-10}$	$\beta=0.846$ $p=4.27 \times 10^{-13}$ $p_{corr}=6.40 \times 10^{-12}$	$\beta=0.827$ $p=3.69 \times 10^{-12}$ $p_{corr}=2.77 \times 10^{-11}$	$\beta=0.804$ $p=3.38 \times 10^{-11}$ $p_{corr}=1.69 \times 10^{-10}$
<i>C_rate_k</i>	GLME (M5)	$\beta=0.513$ $p=1.21 \times 10^{-6}$ $p_{corr}=3.63 \times 10^{-6}$	$\beta=0.676$ $p=0.002$ $p_{corr}=0.005$	$\beta=0.696$ $p=0.003$ $p_{corr}=0.005$	$\beta=0.713$ $p=0.004$ $p_{corr}=0.005$	$\beta=0.690$ $p=0.003$ $p_{corr}=0.005$
<i>Pun_rate_k</i>	GLME (M6)	$\beta=-0.037$ $p=0.802$ $p_{corr}=0.804$	$\beta=-0.066$ $p=0.617$ $p_{corr}=0.771$	$\beta=-0.073$ $p=0.595$ $p_{corr}=0.771$	$\beta=-0.036$ $p=0.804$ $p_{corr}=0.804$	$\beta=-0.057$ $p=0.708$ $p_{corr}=0.804$

Note: $n = 754$, trials (2-30) across all CC dyads; p_{corr} : FDR correction.

M5: $MC \sim C_rate_3 + (1|dyad) + (1|dyad: trial)$, C_rate_3 is proportion of individual cooperation choices across past 3 trials;

M6: $MC \sim Pun_rate_3 + (1|dyad) + (1|dyad: trial)$, Pun_rate_3 is proportion of past 3 trials in which punishment was administered.

b. Statistics of stepwise regressions predicting MC likelihood/speed.

Dependent Variables	Sample size	Statistical test	Test statistics and p values
MC likelihood	$n = 754$, trials (2-30) across all dyads	χ^2 test	Add-model-C1 vs. Final model 1: $\chi^2(1) = 3.765, p = 0.052$
	$n = 490$, trials across all dyads with punishment in history	χ^2 test	Add-model-P1 vs. Final model 1: $\chi^2(1) = 1.13 \times 10^{-5}, p = 0.997$
MC speed	$n = 397$, MC trials (2-30) across all dyads	F-test	Add-model-C2 vs. Final model 2: $F_{(1,394)} = 2.907, p = 0.089$
	$n = 164$, MC trials across all dyads with punishment in history	F-test	Add-model-P2 vs. Final model 2: $F_{(1,161)} = 0.561, p = 0.455$

Final model 1: $MC \sim 1 + MC_rate_3$

Final model 2: $MC \sim 1 + MC_rate_3$

Add-model-C1: $MC \sim 1 + MC_rate_3 + C_rate_3$

Add-model-P1: $MC \sim 1 + MC_rate_3 + Pun_rate_3$

Add-model-C2: $MC \sim 1 + MC_rate_3 + C_rate_3$

Add-model-P2: $MC \sim 1 + MC_rate_3 + Pun_rate_3$

Supplementary Table 4. Full statistical reports for simple reciprocal strategies. GLME: Generalized LME model.

Strategy	Sample size	Statistical test	Test statistics and p values
Tit-for-Tat	$n = 754$, trials (2-30) across all dyads	GLME(S1)	$t_{752} = 4.486, p = 8.41 \times 10^{-6}$, 95% CI : 0.241, 0.615
		Beta comparison	history vs. TFT: 0.846 vs. 0.428: $t = 7.869$; $p = 0.005$
Win-Stay-Lose-Shift		GLME(S2)	$t_{752} = 2.192, p = 0.029$, 95% CI : 0.021, 0.377
		Beta comparison	history vs. WSLS: 0.846 vs. 0.199: $t = 19.620$; $p = 9.45 \times 10^{-6}$

S1: $MC \sim TFT + (1|dyad) + (1|dyad: trial)$, *TFT* is the strategy of copying the partner's previous action; *TFT* is coded 1=MC in last trial, 0=non-MC in last trial;

S2: $MC \sim WSLS + (1|dyad) + (1|dyad: trial)$, *WSLS* is the strategy of repeating one's own previous action following higher reward (MC or unilateral defection); *WSLS* is coded 1=MC/DD in last trial, 0=CD/DC in last trial;

Supplementary Table 5. Full statistics of IBRA analyses. LME: Linear mixed-effect model.

a. Full statistics of IBRA analysis in Fig. 2. and Extended Data Fig. 4

Figure	Sample size	Statistical test	Test statistics and <i>p</i> values
Fig. 2b	<i>n</i> = 141, amygdala channel-pairs	Cluster-based permutation test (n=10,000 times)	MC vs. non-MC: early(70-380ms): $t_{sum} = 119.172$; $p_{corr} = 0.002$; late(480-1160ms): $t_{sum} = 290.572$; $p_{corr} = 1.00 \times 10^{-4}$
			MC vs. zero: early: $t_{sum} = 143.432$; $p_{corr} = 0.001$; late: $t_{sum} = 295.376$; $p_{corr} = 1.00 \times 10^{-4}$
			non-MC vs. zero: early: $t_{sum} = 21.803$; $p_{corr} = 0.227$; late: $t_{sum} = -18.092$; $p_{corr} = 1.000$
	<i>n</i> = 8, CC dyads with amygdala channel-pairs	Dyad level: One-sided paired t-test	MC vs. non-MC: $t_7 = 2.302$, $p = 0.027$, 95% <i>CI</i>: 0.008, Inf
	<i>n</i> = 3134, trials across amygdala channel-pairs	LME (M7)	MC vs. non-MC: $t_{3132} = 6.658$, $p = 3.26 \times 10^{-11}$, 95% <i>CI</i>: 0.196, 0.359
Fig. 2c	<i>n</i> = 332, TPJ channel-pairs	Cluster-based permutation test (n=10,000 times)	MC vs. non-MC: 90-410ms: $t_{sum} = 37.958$; $p_{corr} = 0.135$
			MC vs. zero: 90-410ms: $t_{sum} = 116.610$; $p_{corr} = 0.003$
			non-MC vs. zero: 90-410ms: $t_{sum} = 116.691$; $p_{corr} = 0.003$
Extended Data Fig. 4	<i>n</i> = 141, amygdala channel-pairs	One-sided one-sample t-test	early window: MC-MC trial: $\rho = 0.008$, $t_{140} = 2.391$, $p = 0.009$, $p_{corr} = 0.018$, 95%<i>CI</i>: 0.003, Inf
			NC-NC trial: $\rho = -0.015$, $t_{140} = -3.972$, $p = 1.000$, $p_{corr} = 1.000$, 95% <i>CI</i> : -0.022, Inf
			late window: MC-MC trial: $\rho = 0.010$, $t_{140} = 2.626$, $p = 0.005$, $p_{corr} = 0.018$, 95%<i>CI</i>: 0.004, Inf NC-NC trial: $\rho = -0.002$, $t_{140} = -0.494$, $p = 0.689$, $p_{corr} = 0.918$, 95% <i>CI</i> : -0.007, Inf

M7: IBRA ~ MC + (1|dyad) + (1|dyad: channel-pair), IBRA is time-averaged value across significant time points, MC is coded 1=MC, 0=non-MC;

b. Full statistics of IBRA analysis in Fig. 3.

Figure	Sample size	Statistical test	Test statistics and p values
Fig. 3a	$n = 754$, MC trials across amygdala channel-pairs with identified onset for early IBRA	LME (M8), with FDR correction	Early onset: $\beta = -0.109$, $t_{752} = -2.620$, $p = 0.009$, $p_{corr} = 0.018$, 95% CI: -0.191, -0.027
	$n = 901$, MC trials across amygdala channel-pairs with identified onset for late IBRA		Late onset: $\beta = 0.013$, $t_{899} = 0.380$, $p = 0.704$, $p_{corr} = 0.704$, 95% CI: -0.055, 0.081
	$n = 960$, MC trials across amygdala channel-pairs		Early intensity: $\beta = -0.021$, $t_{958} = -0.553$, $p = 0.580$, $p_{corr} = 0.704$, 95% CI: -0.093, 0.052 Late intensity: $\beta = -0.110$, $t_{958} = -2.856$, $p = 0.004$, $p_{corr} = 0.018$, 95% CI: -0.186, -0.034
	$n = 754$, MC trials across amygdala channel-pairs with identified onset for early IBRA	Mediation analysis (X: MC_rate_3 , M: early IBRA onset, Y: late IBRA intensity)	$a = -0.109$, $p = 0.009$; $b = -0.127$, $p = 9.29 \times 10^{-4}$; $c = -0.110$, $p = 0.004$; $c' = -0.094$, $p = 0.034$; indirect effect = 0.014, $p = 0.012$
Fig. 3b	$n = 960$, MC trials across amygdala channel-pairs	LME (M9, M10), with FDR correction	Early: $\beta = 0.121$, $t_{958} = 3.573$, $p = 3.71 \times 10^{-4}$, $p_{corr} = 7.42 \times 10^{-4}$, 95% CI: 0.054, 0.187 Late: $\beta = 0.169$, $t_{958} = 5.159$, $p = 3.01 \times 10^{-7}$, $p_{corr} = 1.20 \times 10^{-6}$, 95% CI: 0.104, 0.233
Fig. 3c			Early: $\beta = -0.102$, $t_{958} = -3.091$, $p = 0.002$, $p_{corr} = 0.002$, 95% CI: -0.167, -0.037 Late: $\beta = 0.099$, $t_{958} = 3.051$, $p = 0.002$, $p_{corr} = 0.002$, 95% CI: 0.035, 0.162
Fig. 3d	$n = 754$, MC trials across amygdala channel-pairs with identified onset for early IBRA	Mediation analysis (X: MC_rate_3 , M1: early IBRA onset, M2: late IBRA intensity, Y: DDT)	$a = -0.109$, $p = 0.009$; $b_1 = -0.127$, $p = 9.29 \times 10^{-4}$; $b_2 = 0.076$, $p = 0.027$; $c = -0.261$, $p = 2.75 \times 10^{-11}$; $c' = -0.250$, $p = 7.75 \times 10^{-9}$; X-M1-Y: indirect effect = -0.009, $p = 0.020$ X-M2-Y: indirect effect = -0.007, $p = 0.076$ X-M1-M2-Y: indirect effect = 0.001, $p = 0.014$

M8: IBRA onset/intensity $\sim MC_rate_3 + (1|dyad) + (1|dyad: \text{channel-pair})$, MC_rate_3 is proportion of past 3 trials that ended with MC;

M9: $DDT_{sim} \sim \text{IBRA intensity} + (1|dyad) + (1|dyad: \text{channel-pair})$;

M10: $DDT \sim \text{IBRA intensity} + (1|dyad) + (1|dyad: \text{channel-pair})$;

Supplementary Table 6. Full statistics of IBRA analyses when controlling for timing-related confounds. LME: Linear mixed-effect model.

Figure	Sample size	Statistical test	Test statistics and p values
Extended Data Fig. 3a	$n = 3134$, trials across amygdala channel-pairs	window-averaged analysis + LME(M11)	MC vs. non-MC: early: $t_{3130} = 2.923$; $p = 0.003$; late: $t_{3130} = 6.265$; $p = 4.24 \times 10^{-10}$
		LME(M11) with cluster-based permutation test (n=5,000 times)	MC vs. non-MC: early(130-370ms): $t_{\text{sum}} = 70.235$; $p_{\text{corr}} = 0.016$; late(480-1190ms): $t_{\text{sum}} = 282.490$; $p_{\text{corr}} = 2.00 \times 10^{-4}$
Extended Data Fig. 3b	$n = 132$, dDT- and dDTsim-matched amygdala channel-pairs	window-averaged analysis + Paired-sample T-test	MC vs. non-MC: early: $t_{131} = 2.965$; $p = 0.004$; late: $t_{131} = 8.110$; $p = 3.17 \times 10^{-13}$
		Paired-sample T-test with cluster-based permutation test (n=10,000 times)	MC vs. non-MC: early(130-320ms): $t_{\text{sum}} = 56.670$; $p_{\text{corr}} = 0.026$; late(540-1130ms): $t_{\text{sum}} = 370.735$; $p_{\text{corr}} = 1.00 \times 10^{-4}$
Extended Data Fig. 3d	$n = 141$, amygdala channel-pairs	Paired-sample T-test with cluster-based permutation test (n=10,000 times)	MC vs. non-MC: early(1-39bin): $t_{\text{sum}} = 225.339$; $p_{\text{corr}} = 1.00 \times 10^{-4}$; late(49-104bin): $t_{\text{sum}} = 309.857$; $p_{\text{corr}} = 1.00 \times 10^{-4}$

M11: IBRA $\sim$ MC + dDT + dDTsim + (1|dyad) + (1|dyad: channel-pair).

Supplementary Table 7. Full statistics for spectro-spatial dissociation.

a. Spectral profiles of amygdala IBRA in two time windows ($n = 62$, amygdala channels; One-sample t -test, two sided, with FDR correction).

Time window	Test statistics and p values				
	θ	α	β	γ	H- γ
Early	$t_{6I}=-2.919$, $p=0.005$, $p_{corr}=0.025$	$t_{6I}=0.553$, $p=0.582$, $p_{corr}=0.728$	$t_{6I}=0.341$, $p=0.735$, $p_{corr}=0.735$	$t_{6I}=1.632$, $p=0.108$, $p_{corr}=0.180$	$t_{6I}=2.175$, $p=0.034$, $p_{corr}=0.084$
Late	$t_{6I}=-2.632$, $p=0.011$, $p_{corr}=0.018$	$t_{6I}=-3.335$, $p=0.002$, $p_{corr}=0.004$	$t_{6I}=0.140$, $p=0.889$, $p_{corr}=0.889$	$t_{6I}=4.050$, $p=1.47 \times 10^{-4}$, $p_{corr}=0.001$	$t_{6I}=1.354$, $p=0.181$, $p_{corr}=0.226$

Note: θ : 4-8Hz, α : 8-15Hz, β : 15-35Hz, γ : 35-70Hz, H- γ : 70-200Hz;

b. Spatial clustering analyses on different types channel-pairs (Independent -sample t -test, two sided, with FDR correction).

Dependent variables	Sample size	Test statistics and p values
X coordinate	$n = 63$, channel-pairs	early vs. late: $t_{6I}=-0.177$, $p=0.860$, $p_{corr}=0.860$
Y coordinate		early vs. late: $t_{6I}=-2.477$, $p=0.016$, $p_{corr}=0.144$
Z coordinate		early vs. late: $t_{6I}=-2.150$, $p=0.036$, $p_{corr}=0.162$
X coordinate	$n = 23$, channel-pairs	early vs. shared: $t_{2I}=0.333$, $p=0.743$, $p_{corr}=0.836$
Y coordinate		early vs. shared: $t_{2I}=-1.608$, $p=0.123$, $p_{corr}=0.277$
Z coordinate		early vs. shared: $t_{2I}=-1.994$, $p=0.059$, $p_{corr}=0.177$
X coordinate	$n = 52$, channel-pairs	late vs. shared: $t_{50}=0.518$, $p=0.607$, $p_{corr}=0.780$
Y coordinate		late vs. shared: $t_{50}=0.523$, $p=0.604$, $p_{corr}=0.780$
Z coordinate		late vs. shared: $t_{50}=-0.606$, $p=0.547$, $p_{corr}=0.780$

Note: Responsive channel-pairs ($n=69$) were classified as early-selective ($n=17$), late-selective ($n=46$), or shared ($n=6$), depending on whether IBRA increases occurred in the early, late, or both time windows. The MNI coordinates for each channel were extracted, and channels from right and left hemispheres were pooled by taking the absolute values of their x-coordinates. For each channel-pair, the spatial location was represented by the mean MNI coordinates of the two individual channels. The x, y, and z coordinates of early-selective, late-selective, and shared channel-pairs were then compared using two-sided independent-sample t -tests, FDR-corrected for multiple comparisons.

c. Statistics of neural representation of IBRA-related spectral patterns ($n = 282$ amygdala channel-pairs, One-sample t -test, two-sided).

	Test statistics and p values
Fig. 3n	Corr (early spectral similarity, past-MC-rate similarity): $\rho=0.023$, $t_{281}=5.42$, $p=1.28 \times 10^{-7}$, 95% CI: 0.015, 0.031
Fig. 3o	Corr (late spectral similarity, past-MC-rate similarity): $\rho=0.006$, $t_{281}=1.43$, $p=0.15$, 95% CI: -0.002, 0.01
Fig. 3p	Early spectral similarity in MC: $\rho = -0.016$, $t_{281} = -2.804$, $p=0.005$, 95% CI: -0.027, -0.005
Fig. 3q	Late spectral similarity in MC: $\rho = 0.032$, $t_{281} = 6.421$, $p=5.76 \times 10^{-10}$, 95% CI: 0.022, 0.041

Supplementary Table 8. Full statistics in Figure 4. LME: Linear mixed-effect model, GLME: Generalized LME model.

a. Statistics of regressions between model-derived variables and actual behavior.

Figure	Sample size	Statistical test	Test statistics and p values
Fig. 4a	$n = 1140$, clean trials across all CC individuals with variance in cooperation	GLME (M12, M13), with FDR correction	Estimate: $\beta=0.651$, $t_{1136} = 6.123$, $p = 1.26 \times 10^{-9}$, $p_{corr} = 6.55 \times 10^{-9}$, 95% CI : 0.442, 0.859 Uncertainty: $\beta=-0.413$, $t_{1136} = -3.590$, $p = 3.45 \times 10^{-4}$, $p_{corr} = 5.17 \times 10^{-4}$, 95% CI : -0.638, -0.187 PE: $\beta=-0.001$, $t_{1136} = -0.014$, $p = 0.989$, $p_{corr} = 0.989$, 95% CI : -0.133, 0.132
Fig. 4b			Estimate: $\beta=0.656$, $t_{1136} = 6.032$, $p = 2.18 \times 10^{-9}$, $p_{corr} = 6.55 \times 10^{-9}$, 95% CI : 0.443, 0.869 Uncertainty: $\beta=0.108$, $t_{1136} = 0.989$, $p = 0.323$, $p_{corr} = 0.388$, 95% CI : -0.106, 0.321 PE: $\beta=0.371$, $t_{1136} = 5.427$, $p = 6.99 \times 10^{-8}$, $p_{corr} = 1.40 \times 10^{-7}$, 95% CI : 0.237, 0.506
Fig. 4a		GLME (M14)	Estimate: $\beta=0.625$, $t_{1135} = 5.819$, $p = 7.69 \times 10^{-9}$, 95% CI : 0.414, 0.835 Uncertainty: $\beta=-0.420$, $t_{1135} = -3.652$, $p = 2.72 \times 10^{-4}$, 95% CI : -0.645, -0.194 PE: $\beta=-0.017$, $t_{1135} = -0.251$, $p = 0.802$, 95% CI : -0.152, 0.117

M12: $P_D \sim \text{Estimate} + \text{Uncertainty} + \text{PE} + (1 | \text{individual})$, Estimate/Uncertainty/PE is derived from *self-and-other-history* model, P_D is the current decision of partner, P_D is coded 1=cooperate, 0=defect.

M13: $S_D \sim \text{Estimate} + \text{Uncertainty} + \text{PE} + (1 | \text{individual})$. S_D is the current decision of self, S_D is coded 1=cooperate, 0= defect

M14: $P_D \sim \text{Estimate} + \text{Uncertainty} + \text{PE} + S_D + (1 | \text{individual})$

b. Statistics of spectrotemporal features predicting self/partner decision.

Figure	Sample size	Statistical test	Test statistics and p values
Fig. 4c (left)	$n = 1593$, clean trials across individual amygdala channels	GLME (M15, M16), with FDR correction	M15: $\beta = -0.131$, $t_{1590} = -2.290$, $p = 0.022$, $p_{corr} = 0.044$, 95% CI: -0.243, -0.019 M16: $\beta = 0.113$, $t_{1590} = 1.935$, $p = 0.053$, $p_{corr} = 0.080$, 95% CI: -0.002, 0.227
Fig. 4c (right)			M15: $\beta = -0.173$, $t_{1590} = -2.947$, $p = 0.003$, $p_{corr} = 0.012$, 95% CI: -0.288, -0.058 M16: $\beta = -0.042$, $t_{1590} = -0.720$, $p = 0.472$, $p_{corr} = 0.472$, 95% CI: -0.157, 0.073
Fig. 4d			M15: $\beta = 0.042$, $t_{1590} = 0.753$, $p = 0.452$, $p_{corr} = 0.472$, 95% CI: -0.067, 0.150 M16: $\beta = 0.183$, $t_{1590} = 2.857$, $p = 0.004$, $p_{corr} = 0.012$, 95% CI: 0.057, 0.308

M15: $P_D \sim \text{Power} + S_D + (1 | \text{individual}) + (1 | \text{individual: channel})$, Power is mean value of three spectral features in Fig. 3e-h, P_D (S_D) is the current decision of partner (self), P_D/S_D is coded 1=cooperate, 0=defect.
M16: $S_D \sim \text{Power} + P_D + (1 | \text{individual}) + (1 | \text{individual: channel})$.

c. Statistics of spectrotemporal features encoding model-derived variables.

Figure	Sample size	Statistical test	Test statistics and p values
Fig. 4e	$n = 1593$, clean trials across individual amygdala channels	LME (M17), with FDR correction	Estimate: $\beta = -0.121$, $t_{1589} = -3.436$, $p = 6.05 \times 10^{-4}$, $p_{corr} = 0.005$, 95% CI: -0.190, -0.052 Uncertainty: $\beta = -0.079$, $t_{1589} = -2.403$, $p = 0.016$, $p_{corr} = 0.032$, 95% CI: -0.144, -0.015 PE: $\beta = 0.038$, $t_{1589} = 1.473$, $p = 0.141$, $p_{corr} = 0.181$, 95% CI: -0.013, 0.089
Fig. 4f			Estimate: $\beta = -0.084$, $t_{1589} = -1.809$, $p = 0.071$, $p_{corr} = 0.106$, 95% CI: -0.175, 0.007 Uncertainty: $\beta = -0.120$, $t_{1589} = -2.723$, $p = 0.007$, $p_{corr} = 0.030$, 95% CI: -0.206, -0.033 PE: $\beta = 0.064$, $t_{1589} = 2.448$, $p = 0.015$, $p_{corr} = 0.032$, 95% CI: 0.013, 0.115
Fig. 4g			Estimate: $\beta = 0.006$, $t_{1589} = 0.133$, $p = 0.894$, $p_{corr} = 0.894$, 95% CI: -0.077, 0.089 Uncertainty: $\beta = -0.021$, $t_{1589} = -0.528$, $p = 0.598$, $p_{corr} = 0.673$, 95% CI: -0.098, 0.057 PE: $\beta = 0.062$, $t_{1589} = 2.373$, $p = 0.018$, $p_{corr} = 0.032$, 95% CI: 0.011, 0.114

M17: $\text{Power} \sim \text{Estimate} + \text{Uncertainty} + \text{PE} + (1 | \text{individual})$

Supplementary Table 9. Trait-level differences between CC and pMC dyads. For each trait, the average score of both patients within each dyad was computed and compared between CC and pMC dyad type (independent-sample *t*-test, two-sided, FDR corrected). IUS: intolerance of uncertainty scale, SVO: social value orientation, IRI: interpersonal reactivity index. 8/4/7 dyads failed to complete the IUS/SVO/IRI measurements, respectively.

Traits	Dyad type	Sample size	Mean (S.D.)	Test statistics and <i>p</i> values
Uncertainty tolerance (IUS)	CC dyads	22	47.023 (10.442)	$t_{35}=-3.731$, $p=6.75 \times 10^{-4}$, $p_{corr}=0.002$, 95% CI = -23.951, -7.070
	pMC dyads	15	62.533 (14.895)	
Social preference (SVO)	CC dyads	24	24.454 (7.624)	$t_{39}=-0.154$, $p=0.878$, $p_{corr}=0.878$, 95% CI = -5.145, 4.416
	pMC dyads	17	24.820 (7.207)	
Empathic concern (IRI)	CC dyads	23	3.206 (0.283)	$t_{36}=0.640$, $p=0.526$, $p_{corr}=0.789$, 95% CI = -0.144, 0.278
	pMC dyads	15	3.139 (0.356)	

References for supplementary information

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