

¹ Supplementary Material

² Signalling boosts the evolution of cooperation in repeated group
³ interactions

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⁵ In this Supplementary Material we further elaborate on the methods and results discussed in the main text.
⁶ In Section S1, we provide an additional details on the analytical and numerical procedures employed. In Section
⁷ S2, we detail the nature of the strategies in each drifting group. We show further evidence of the robustness
⁸ of our conclusions in Section S3, providing extended analyses and discussion of the whole parameter space.
⁹ Finally, in Section S4 we deduce analytically the conditions under which some significant strategies are more
¹⁰ likely to be invaded by others.

¹¹ **S1. Extended Methods**

¹² As detailed in the main text, we consider a finite population of Z individuals, which form random groups of size
¹³ N . Within each group, individuals interact through a non-linear and stochastic N -player iterated game. As we
¹⁴ detail in the following sections, we present a finite population model of evolution, in which the proportion of time
¹⁵ spent at equilibria can be explicitly calculated. We consider that individuals revise their behaviour by social
¹⁶ learning, such that individuals with higher fitness will tend to be imitated more often. Here, fitness is given by
¹⁷ the average payoff obtained from a large number of N -player interactions. Given the large number of different
¹⁸ strategies (2^6 for **S+R**), our analysis can be simplified by adopting the limit of rare mutations, corresponding
¹⁹ to maximal reduction of configurations of interest in a hierarchy of possible approximations [1, 2, 3, 4]. Under a
²⁰ process of imitation dynamics, only a new mutation can introduce a new strategy and, whenever mutations are
²¹ rare, new strategies will either invade a resident population or become extinct. Thus, assuming that mutations
²² take place much slower than the reproductive or imitation dynamics, as we describe later, there exist a maximum
²³ number of two strategies A and B at the same time in the population. We denote as N_Λ and Z_Λ the number
²⁴ of individuals of type $\Lambda \in \{A, B\}$ in the group and population, respectively, such as $N_A + N_B = N$ and
²⁵ $Z_A + Z_B = Z$.

²⁶ **Game payoffs and strategy space**

²⁷ We first assume that the ecological context is in one of two states L : a public good game state G with probability
²⁸ λ and a non public good game \tilde{G} with probability $1 - \lambda$. In each round, individuals may decide to contribute
²⁹ a value to a common pool (to Cooperate, C) or refuse to contribute (to defect, D). In the G state, a collective
³⁰ benefit is produced to the extent that at least $N_C \geq M$ individuals contributed to the public good, where M
³¹ represents a coordination threshold. In this case, each member of the group obtains a benefit $b = rcN_C/N$,
³² with c the cost of cooperating, N_C the number of cooperators, and $r > 1$ the multiplication factor. If $N_C < M$
³³ no collective benefit is produced, and all receive 0.

³⁴ In **S+R**, behavioural strategies represent under what condition individuals will act in one or another way.
³⁵ We assume that individuals make two decisions within each round of the game:

- ³⁶ • *Signalling.* First individuals decide if they signal (S) or not (\tilde{S}). Signalling comes with a cost c_S . This
³⁷ decision is only based on the current ecological context, hence it is encoded by two bits in the strategy

space s_α , with $\alpha \in \{G, \tilde{G}\}$. If more than a given number Q of individuals in the group signal, we say that the quorum was reached and the group is signalling.

- *Acting.* After the signalling phase, individuals decide whether to cooperate (C) or defect (D). Cooperation comes with an individual cost c , whereas defecting is free. In this phase, the decision is made taking into account if the group reached the signalling quorum and if at least M individuals cooperated in the previous round. Therefore four bits characterise this decision in the strategy space $a_{\gamma, \gamma'}$, with $\gamma \in \{Q, \tilde{Q}\}$ and $\gamma' \in \{M, \tilde{M}\}$ representing all combinations from the achievement—or not—of the signalling quorum (γ) and the attainment—or not—of the cooperation threshold (γ'). Note that in the count of individuals that cooperated is also included the focal player; we also analysed the scenario where the focal player excludes herself from this count (see below).

In summary, strategies are given by six bits $\{s_G, s_{\tilde{G}}; a_{\tilde{Q}, M}, a_{\tilde{Q}, \tilde{M}}, a_{Q, M}, a_{Q, \tilde{M}}\}$. We restrain our analysis to pure strategies, *i.e.* $s_\alpha, a_{\gamma, \gamma'} \in \{\epsilon, 1 - \epsilon\}$, where ϵ represents the small probability that an individual commits an error, that is, chooses the opposite option that she intends to. In order to make easier the notation we will write strategies just using 0 and 1 instead of ϵ . For example, an individual playing the strategy [100011] signals only when in G and cooperates only if the group was signalling (no matter if the threshold M was reached in the previous round); on the contrary an individual with the strategy [001010] never signals but cooperates if enough individuals M cooperated in the previous round, neglecting signals.

The payoff that each individual obtains in a given round of the repeated game is the sum of the benefit (if any) and the costs of signalling and cooperating (if she decides to do so). Since a game is played for multiple rounds, the action of a player in a round may be influenced by the actions of the group in the previous round. If we consider two strategies, A and B, the iterative process can be described as a Markov chain with a stochastic matrix \mathbf{A} whose elements A_{ij} represent the transition probabilities between states i and j in a group formed by N_A and N_B individuals. Each state represents the number of individuals of each type that cooperates in a given round $(N_{C,A}(i), N_{C,B}(i))$ (with $N_C(i) = N_{C,A}(i) + N_{C,B}(i)$) and then the parameter space can be written as $\{0, \dots, N_A\} \times \{0, \dots, N_B\}$.

Given the stochastic nature of this repeated game and errors associated, for a large number of rounds (*i.e.* the probability of playing a new round is $\omega = 1$), initial conditions are not important since all possible states are eventually visited. In this situation, the probability \mathbf{p}^L that the system is found in state \mathbf{p}_i for a given ecological context L just corresponds to the normalised eigenvector associated with the first eigenvalue of \mathbf{A}^L [5]. On the other hand, if the number of rounds are finite ($\omega < 1$), the probability \mathbf{p}^L is computed as follows:

$$\mathbf{p}^L = (1 - \omega) \mathbf{p}^0 (\mathbf{I} - \omega \mathbf{A}^L)^{-1} \quad (1)$$

where \mathbf{I} is the identity matrix and \mathbf{p}^0 the vector with the probabilities of the initial states. The length of each dimension of these matrices and vectors are $(N_A + 1)(N_B + 1)$. We assume that the initial conditions in this game is $p_i^0 = \epsilon N_C(i) + (1 - \epsilon)(N - N_C(i))$ independently of the ecological context. In other words, all individuals begin defecting (except for errors). This choice—although seemingly arbitrary—represents the case in which the group is presented with a new instance of the problem and has no prior knowledge to exploit. In such conditions, agents cannot rely on any memory about the outcome of previous interactions, equivalent to the state in which the cooperation threshold was not reached.

The transition probabilities A_{ij} can be expressed as

$$A_{ij} = Pr^A(i, j) Pr^B(j, i), \quad (2)$$

where $Pr^\Lambda(i, j)$ stands for the probability that $N_{C,\Lambda}(j)$ individuals cooperate out of the N_Λ that are in the group, corresponding then to the probability mass function of the binomial distribution:

$$Pr^\Lambda(i, j) = \binom{N_\Lambda}{N_{C,\Lambda}(j)} P_C^\Lambda(i)^{N_{C,\Lambda}(j)} (1 - P_C^\Lambda(i))^{N_\Lambda - N_{C,\Lambda}(j)}, \quad (3)$$

which is a function of the probability $P_C^\Lambda(i)$ that an individual following strategy Λ cooperates when in state i . This probability depends on whether the thresholds Q and M were reached and how the individual reacts according to her strategy:

$$\begin{aligned} P_C^\Lambda(i) = & \Theta(N_S - Q) \Theta(N_C(i) - M) a_{Q,M}^\Lambda \\ & + \Theta(N_S - Q) [1 - \Theta(N_C(i) - M)] a_{Q,\tilde{M}}^\Lambda \\ & + [1 - \Theta(N_S - Q)] \Theta(N_C(i) - M) a_{\tilde{Q},M}^\Lambda \\ & + [1 - \Theta(N_S - Q)] [1 - \Theta(N_C(i) - M)] a_{\tilde{Q},\tilde{M}}^\Lambda, \end{aligned} \quad (4)$$

81 where $\Theta(x)$ stands for the Heaviside step function, *i.e.* $\Theta(x) = 1$ if $x \geq 0$ and 0 otherwise. Note that \mathbf{A} is
 82 different if individuals exclude themselves in the count of the threshold for reaching the cooperation threshold
 83 M (see below for an alternative).

84 The average payoff per round that a k -strategist obtains in the group under the ecological context is
 85 $W_{\Lambda}^L(N_A, N_B) = \mathbf{w}_{\Lambda}^L \cdot \mathbf{p}^L$, where \mathbf{w}_{Λ} corresponds to the vector with the payoffs of each possible state for
 86 the player with strategy Λ :

$$w_{\Lambda,i}^L = rc \frac{N_C(i)}{N} \Theta(N_C(i) - M) - c \frac{N_{C,k}(i)}{N_{\Lambda}} - c_S s_L^{\Lambda}, \quad (5)$$

87 Finally, the average payoff of an individual with strategy Λ taking into account both ecological contexts is
 88 $W_{\Lambda}(N_A, N_B) = \lambda W_{\Lambda}^G(N_A, N_B) + (1 - \lambda) W_{\Lambda}^{\tilde{G}}(N_A, N_B)$.

89 Evolutionary dynamics

90 Once the average payoff per round $W_{\Lambda}(N_A, N_B)$ is obtained, we compute the average payoff Π_{Λ} over all the
 91 possible group combinations [6, 7, 8, 9]:

$$\Pi_{\Lambda} = \sum_{N_{\Lambda}=1}^{\min(N, Z_{\Lambda})} H(N_{\Lambda} - 1, N - 1, Z_{\Lambda} - 1, Z - 1) W_{\Lambda}(N_A, N_B), \quad (6)$$

92 where the hypergeometric distribution can be expressed as

$$H(N_{\Lambda}, N, Z_{\Lambda}, Z) = \frac{\binom{Z_{\Lambda}}{N_{\Lambda}} \binom{Z - Z_{\Lambda}}{N - N_{\Lambda}}}{\binom{Z}{N}}. \quad (7)$$

93 In order to simplify the evolutionary dynamics analysis, we adopt the small mutation approximation [1].
 94 Under this approximation, whenever a mutant (an invader) appears in a resident population, two possible final
 95 scenarios occur before any other mutation takes place: the mutant trait fixates in the population (it is imitated
 96 by all residents) or mutants are expelled (they imitate the resident strategy). In either case, the final state
 97 is monomorphic and no mixed state is considered, which could lead to a much more complex ecosystem of
 98 strategies [10, 4]. The transition probability between pairs of strategies is determined as a fixation probability,
 99 *i.e.* the probability that a single mutant with a strategy j invades a population formed by $Z - 1$ individuals
 100 that follow a strategy i [11, 1, 2]:

$$\rho_{ij} = \left(1 + \sum_{m=1}^{Z-1} \prod_{k=1}^m \frac{T^-(k)}{T^+(k)} \right)^{-1}, \quad (8)$$

101 where $T^+(k)$ is the probability that an individual of the resident strategy i imitates a mutant j and $T^-(k)$ is
 102 the probability that an individual of the mutant strategy j imitates a resident i in a population of k individuals
 103 playing the resident strategy. Assuming a Fermi probability function for pairwise strategy imitation [12], these
 104 probabilities are given by

$$T^{\pm}(k) = \frac{k(Z - k)}{Z^2} \left(1 + e^{\mp \beta [\Pi_j(k) - \Pi_i(k)]} \right)^{-1}, \quad (9)$$

105 where β represents the intensity of selection, *i.e.*, the strength individuals base their decision to imitate the
 106 others.

107 In the case of neutral drift, the fixation probability among all pairs of strategies is $\rho_{ij} = \eta = 1/Z$. The
 108 probabilities defined by Eq (8) determine a transition matrix of a Markov chain among strategies, assuming a
 109 sufficiently low mutation rate [13]. The non-diagonal elements of this matrix are $\mathcal{T}_{ij} = \rho_{ij}\nu^{-1}$, and the diagonal
 110 is $\mathcal{T}_{ii} = 1 - \sum_j \mathcal{T}_{ij}$, where ν is the total number of strategies. The normalised eigenvector associated with the
 111 first eigenvalue of that matrix provides the stationary distribution D_i of strategies [14, 1], which represents the
 112 relative time the population spends adopting strategy i . The transition probability $\mathcal{G}_{g_i g_j}$ between two groups
 113 of strategies g_i and g_j is computed as:

$$\mathcal{G}_{g_i g_j} = \sum_{i \in g_i, j \in g_j} \mathcal{T}_{ij} \frac{D_i}{\sum_{k \in g_i} D_k} \quad (10)$$

114 Drifting groups

115 In order to analyse the specific dynamics and success of the different strategies, we identify groups of strategies
 116 that show equivalent behaviour. Strategies [00 ** $\alpha_1 \alpha_2$] and [11 $\alpha_1 \alpha_2$ **] formed 8 groups (for each combination
 117 of α_i , and varying * within each group) whose strategies show neutral drift among them if the noise in signal is

low enough. Specifically, when approximately $\epsilon < Q/N$ and $\epsilon < 1 - Q/N$ for the first and second set of groups, respectively, since the actual average number of individuals that signal in a group is $N_S - (2N_S - N)\epsilon$ when N_S of them intend to do it. In our analysis we assume $\epsilon = 0.01$, therefore the previous groups are drifting groups (except for $Q = N$ for the second set of groups). This does not mean that the probabilities of the strategies within a drifting group in the stationary distribution are the same, since, as we show, there usually exist some strategies that are able to invade others more successfully.

Since the initial conditions of the iterated game assume that all individuals begin defecting, except because of noise, strategies $[\alpha_1\alpha_2\ 10\alpha_3\alpha_4]$ are equivalent to $[\alpha_1\alpha_2\ 00\alpha_3\alpha_4]$, and $[\alpha_1\alpha_2\ \alpha_3\alpha_410]$ to $[\alpha_1\alpha_2\ \alpha_3\alpha_400]$, if the noise is low and the threshold M is high enough to prevent that the bit that differentiates them plays any role. The probability that less than M individuals commit an error acting due to noise in one round follows the binomial cumulative distribution function:

$$Pr_\epsilon(< M) = \sum_{k=0}^{M-1} \binom{N}{k} \epsilon^k (1-\epsilon)^{N-k}. \quad (11)$$

The probability that this happens in every round of the game (except the last one, in which case it would not have any effect) is $[Pr_\epsilon(< M)]^{\mathcal{R}-1}$, where $\mathcal{R} = (1 - \omega)^{-1}$ is the average number of rounds of the game. Note that it would be possible that in a round M is reached but in the next, again due to errors, individuals that would have started to cooperate defect again, correcting the first errors. This is the reason why, even when $\omega = 1$ and all the states can be reached, these drifting groups still appear, as we have seen in our analysis.

Alternative scenarios

Our model includes strategies that can decide their action taking into account if the number of individuals that cooperated in the past is higher or lower than the threshold M . We also analysed a scenario where—instead of using memory of past interactions—individuals base their decision on the actual reception of a benefit. We refer to this case as the *benefit-perceived scenario*. The model remains the same, except when the ecological context is \tilde{G} . There exist two main possible interpretations of \tilde{G} : a scenario without resources or a scenario with abundance. In the former, individuals are not obtaining any benefit (equivalent in the regular scenario to consider that M was not reached), whereas in the latter every individual obtains a benefit (equivalent to consider that M is always reached).

A second alternative scenario is introduced to study the effects of self-awareness. So far, we have assumed that individuals can base their action on the number of individuals that cooperated within the group in the previous round (i.e., if the threshold M was reached) without removing themselves from this counting. In the *self-aware scenario*, we introduce another parameter $R \in [1, N-1]$, that stands for the number of individuals other than the focal player that cooperated in the previous round, and serves as a threshold for the individuals to decide their current action. As a consequence, R can be different from M , which represents the number of individuals needed to obtain the benefit. The strategy space is modified in its acting module as $a_{\gamma,\gamma'}$, where now $\gamma' = \{R, \tilde{R}\}$. As a consequence, \mathbf{A} also changes since $Pr^k(i, j)$ corresponds now to the probability mass function of the Poisson binomial distribution [15], i.e., the probability that $N_{C,k}(j)$ k -individuals cooperate among the total N_k in the group, considering that the probability of cooperation of each individual is $P_{C|C}^k(i)$ for $N_{C,k}(i)$ of them and $P_{C|D}^k(i)$ for the remaining $N_k(i) - N_{C,k}(i)$ ones, where

$$\begin{aligned} P_{C|C}^k(i) &= \Theta(N_S - Q) \Theta(N_C(i) - 1 - R) a_{Q,R}^k \\ &\quad + \Theta(N_S - Q) [1 - \Theta(N_C(i) - 1 - R)] a_{Q,\tilde{R}}^k \\ &\quad + [1 - \Theta(N_S - Q)] \Theta(N_C(i) - 1 - R) a_{\tilde{Q},R}^k \\ &\quad + [1 - \Theta(N_S - Q)] [1 - \Theta(N_C(i) - 1 - R)] a_{\tilde{Q},\tilde{R}}^k \\ P_{C|D}^k(i) &= \Theta(N_S - Q) \Theta(N_C(i) - R) a_{Q,R}^k \\ &\quad + \Theta(N_S - Q) [1 - \Theta(N_C(i) - R)] a_{Q,\tilde{R}}^k \\ &\quad + [1 - \Theta(N_S - Q)] \Theta(N_C(i) - R) a_{\tilde{Q},R}^k \\ &\quad + [1 - \Theta(N_S - Q)] [1 - \Theta(N_C(i) - R)] a_{\tilde{Q},\tilde{R}}^k. \end{aligned} \quad (12)$$

S2. Representative groups of strategies

Among all the possible strategies that can use signalling and reciprocity (condition **S+R**), we have identified the strategies and drifting groups of strategies (i.e, groups in which strategies show neutral drift among them)

157 that are the most representative in the stationary distributions for a wide range of parameters. Here we describe
158 these groups with more detail (see the main text for a summary):

- *Signalling to cooperate (**SC**)*: strategy [10 0011] signals under state G and cooperates when the group signals. Strategies [10 1011] joins the prototype in a drifting group if M is high enough.
- *Signalling to defect (**SD**)*: strategy [01 1100] signals under state \tilde{G} and only cooperates if the group is not signalling. **SD** is symmetric to **SC**, and in a similar way, strategy [10 1110] forms a drifting group with it for high values of M .
- *Signalling to cooperate and opportunistic (**SC-O**)*: strategy [10 0001] is similar to the prototype of **SC**, but when it is time to cooperate, it only does it if M was not reached previously.
- *Signalling to defect and opportunistic (**SD-O**)*: strategy [01 0100] shows the same relation with **SD** as **SC-O** with **SC**.
- *Free-riding in signalling but using the lack of signalling to cooperate (**FR-C**)*: strategy [00 1100] acts similarly as **SD** but does not signal under any circumstance. It constitutes a drifting group with [00 11**] strategies.
- *Free-riding in signalling and pure defecting (**FR-D**)*: strategy [00 0000] is the pure defector; it does not signal neither cooperates. It is part of the drifting group [00 00**].
- *Free-riding in signalling and opportunistic (**FR-O**)*: strategy [00 0100] behaves as **SD-O** without signalling. Its drifting group is [00 01**].
- *Free-riding in signalling and following (**FR-F**)*: strategy [00 1000] do not signal and cooperates only if the group was also not signalling and the M was previously reached. Its drifting group is [00 01**]. This group also drifts with **FR-C** when M is low, and with **FR-D** when M is high enough. It only appears independently under the benefit-perceived scenario.

179 One can see that all these important groups use the information from signals to decide how to act (except
180 the full defector **FR-D**). However only some of them contribute actively using signals under G or \tilde{G} (**SC**, **SD**,
181 **SC-O**, and **SD-O**); the rest just exploit signals for action, without paying the costs of signalling (**FR-C**, **FR-D**,
182 **FR-O**, and **FR-F**). Some of these strategies combine this information with reciprocity (**SC-O**, **SD-O**, **FR-O**
183 and **FR-F**), but none of them use only reciprocity to make their decisions.

184 S3. Influence of parameters of the model

185 **Emergence of signalling strategies.** For moderate c_S , signalling is exploited and acquires a clear meaning,
186 standing for the identification of rare ecological conditions. This is clearly visible in Fig. 2 of the main text
187 for $M = 5$ (see also Fig. S2 for $M = 7$), which shows the prevalence of all the signalling strategies within the
188 $\{\lambda, c_S\}$ parameter space, while the dominating groups are displayed in Fig. 4 of the main text and also Fig. S5
189 for a finite number of rounds ($\omega = 0.9$). When c_S is negligible, strategies that exploit signals to cooperate (i.e.,
190 **SC** or **SC-O**) and to defect (**SD** or **SD-O**) dominate equally. This is also visible in the invasion graphs from
191 Fig. S4a and S4b, in which we note also that the two signalling strategies do not invade each other, as a result
192 of the different meaning associated to signals which prevents their coexistence. When c_S takes a non-null but
193 low value, **SC** and **SC-O** prevail for lower values of λ , while **SD** and **SD-O** dominate for higher ones, since
194 it is less costly to signal for the less frequent ecological condition. However this symmetry is quickly broken:
195 whereas **SC** and **SC-O** continue dominating when $\lambda \leq 0.5$, **SD** and **SD-O** disappear quickly (see also the
196 invasion graphs in Fig. S4c and S4d). Interestingly, unless λ is close to an extreme, **SC** and **SD** never invade
197 each other, neither do **SC-O** and **SD-O** (at least not with a probability higher than the neutral drift): the
198 success of one or the other are the result of the interaction with other strategies, especially those that free-
199 ride the signalling costs (see Fig. S4). The asymmetric benefit for different environmental conditions result in
200 asymmetries in the strategies, so that signalling for the unprofitable conditions results in lower advantage, and
201 is therefore subsumed by strategies that mostly cooperate but free ride the signalling cost (see below). Given
202 that coexistence of signals with different meaning is not possible, different signalling strategies mostly appear
203 in isolation.

204 **Free-riding on signalling costs.** When c_S takes high values, strategies that dominate do not signal under
 205 any circumstance and only specify their actions, coherently, when the quorum in signalling was not reached.
 206 Depending on the frequency of each ecological condition, these actions may differ. When λ is not high, **SC** and
 207 **SC-O** eventually become too expensive and **FR-D** (full defection) takes their place, since cooperation becomes
 208 a cost not worthy to be paid for the few chances of obtaining a benefit in the G state (see also Fig. S4e). On the
 209 other hand, **FR-C** prevails over **SD** even for moderate values of c_S , because both employ the same strategy to
 210 act (i.e., cooperate when there is no signal), but the former does not pay any cost for signalling (see Fig. S4h).
 211 **FR-D** cannot exploit **SC** in the same way because the latter cooperates only when the signalling quorum is
 212 attained, while in the absence of signalling, no benefit is obtained. Hence, **FR-D** cannot obtain any benefit by
 213 only free-riding the costs of signalling, and dominates only when c_S is too high. Note that **FR-D** hardly ever
 214 invades **SC** in Fig. S4. On the contrary, **SC** does invade **FR-D** for moderate-low values of c_S , as discussed
 215 before. In between **FR-C** and **FR-D**, there appears the opportunistic strategy **FR-O**. An individual playing
 216 **FR-O** within a cooperative group acts as a defector. Conversely, among defectors, **FR-O** cooperates. It may
 217 look like a counter-intuitive behaviour, but this strategy allows to exploit cooperators, recognising when the
 218 own contribution is not necessary to obtain the benefit, and if not enough individuals cooperate, **FR-O** makes
 219 an effort to sum up enough cooperators. This elaborated behaviour has the objective to maximise the number
 220 of times a benefit is obtained, but working for it as less as possible. When individuals of an homogeneous
 221 population follow this strategy, they will cooperate half of the time. This behaviour only pays when the G
 222 state appears with a high frequency, otherwise defectors **FR-D** take over (see also Fig. S4f and S4g). Overall,
 223 a general pattern among strategies that share the same signalling behaviour can be found: **FR-O** can invade
 224 **FR-C** and **FR-D** can invade both, but never in the opposite direction (see Fig. S4). The same happens with
 225 **SC-O** invading **SC**, and **SD-O** invading **SD**. As observed in other studies based on public good games, there
 226 exist an evolutionary tendency to defection when the benefits-cost trade-off is not benign. Cooperative strategies
 227 become successful when they can invade other strategies with a different signalling behaviour, keeping defectors
 228 at bay without directly invading defectors that share the same signalling behaviour.

229 **Cooperation threshold and signalling quorum.** Thresholds M and Q have a significant role in the dy-
 230 namics of the system. Fig. 4 in the main text and Fig. S5 show how M plays a fundamental role. Cooperation
 231 is favoured with the increase of M : cooperative strategies (**SC**, **SD**, and **FR-C**) dominate over their oppor-
 232 tunistic counterparts (namely, **SC-O**, **SD-O** and **FR-O**) when $M > 5$, while full defection (**FR-D**) dominates
 233 across large portions of the parameter space for low values of M . Indeed, higher values of M impose stronger
 234 constraints for cooperation in order to receive a benefit. In such conditions, **SC-O** and **SD-O** are not able
 235 to invade **SC** and **SD**, respectively, since an unconditional cooperative strategy that is based on signalling
 236 only is more advantageous than the conditional counterpart. The impact of the threshold Q is less important.
 237 Intermediate values of Q are better for **SC**. The presence of **SC-O**, on the other hand, increases with Q when
 238 the requirements for cooperation are mild ($3 \leq M \leq 7$). This happens when the system has enough time to
 239 self-organise, but not when the number of rounds is limited, as shown in Fig. S5. Both **FR-C** and **FR-O**
 240 lose importance against defectors playing **FR-D** when Q increases since it is more difficult that the signalling
 241 quorum is reached when Q is high.

242 As already suggested in the discussion above, the thresholds M and Q are strongly related the probability
 243 of making errors with respect to what dictated by the strategy. For instance, M can be interpreted as the
 244 effectiveness of cooperation against errors. An increase in the error probability can be represented by an increase
 245 of the cooperation threshold M , because individuals that cooperate may not effectively contribute to reach the
 246 threshold due to frequent errors in their actions. Under this interpretation, **FR-O** is less successful because
 247 higher cooperation thresholds/errors jeopardise the positive contribution towards reaching the threshold, leading
 248 to less occasions for opportunistic behaviour and overall lower payoff. In the same way, when individuals commit
 249 errors in assessing the signalling behaviour, reaching the signalling quorum Q is more difficult, hence we can
 250 interpret higher errors as a larger quorum. When Q is low, the signalling quorum may be reached due to errors
 251 even when in \tilde{G} , leading **SC** and **SC-O** to cooperate without obtaining any benefit. With signalling, we can
 252 consider also another source of error, that is, using the signal in the wrong ecological condition. This error
 253 ϵ_S represents the inability of individuals to correctly discriminate G from \tilde{G} , so that a signal is produced with
 254 probability $(1 - \epsilon_S)s_\alpha + \epsilon_S s_{\bar{\alpha}}$. This type of error could undermine the success of **SC** or **SD**, which trust in the
 255 correct assessment of the ecological context to decide whether or not to cooperate. However, results show that
 256 the signalling strategies are rather robust against this kind of error, thanks to the aggregation of information
 257 from multiple individuals and to the quorum mechanism. As a matter of fact, a rather high value of ϵ_S is
 258 necessary to observe some effect, as can be seen in Fig. S6.

259

260 **S4. Invasibility preference**

261 The evolutionary process leading to the emergence of one or the other strategy is very complex, as shown by the
 262 invasibility graphs in Fig. S4, because every strategy plays a role, even when its probability in the stationary
 263 distribution is low. In spite of this, it is possible to deduce the conditions under which a given strategy is
 264 more likely to replace another strategy than *vice versa*. Due to the complexity of the strategies themselves, we
 265 focus only on the conditions on c_S and λ for those pairs of strategies where both members emerge for the same
 266 combination of the other parameters. The preference on the direction of the invasibility between two strategies
 267 does not guarantee that the preferred strategy has higher probability in the stationary distribution due to the
 268 influence of the rest of the strategies. Therefore this analysis should be taken as a way to corroborate the results
 269 that were already discussed.

270 In the limit of large population size Z , strategy A replaces B in the population if

$$\sum_{N_A=1}^N W_A(N_A, N_B) > \sum_{N_A=0}^{N-1} W_B(N_A, N_B), \quad (13)$$

271 where $W_\Lambda(N_A, N_B)$ is the payoff that a focal player following strategy Λ obtains in a group of size N formed
 272 by N_A individuals playing strategy A and $N - N_B$ playing strategy B [16]. We apply this condition for some
 273 significant pairs of strategies (A, B) assuming that $\epsilon \rightarrow 0$, $M, Q = \{1, \dots, N-1\}$ are integers (the closest greater
 274 integer is taken when the original parameter was not an integer), $\omega = 1$, and $c = 1$, obtaining the following
 275 conditions:

- 276 • **(SC, FR-D):** $c_S < \left(\frac{r}{N} - 1\right) + \left(\frac{Q-1}{N}\right)$
- 277 • **(SC-O, FR-D):** $c_S < \frac{1}{2} \left[\left(\frac{r}{N} - 1\right) + \left(\frac{Q-1}{N}\right) - \frac{\max\{0, M-Q\}}{N} \right]$
- 278 • **(FR-C, FR-D):** $\lambda > \frac{N}{r}$
- 279 • **(FR-O, FR-D):** $\lambda > \frac{N+M-1}{r}$
- 280 • **(SC, SC-O) and (SD, SD-O):** $r - 2N + M > 0$
- 281 • **(SC, FR-C):** $\frac{1}{\lambda} - c_S > \frac{2(N-Q)+1}{N}$
- 282 • **(SD, FR-C):** $c_S < \frac{1}{N}$
- 283 • **(FR-O, FR-C):** $\lambda < \frac{2N-M}{r}$
- 284 • **(SC, SD):** $\left(\lambda - \frac{1}{2}\right) c_S < \frac{2Q-N-1}{2N}$

285 These conditions generally match the qualitative behaviour observed in Fig. S4 and discussed in Section S3.
 286 Quantitative differences, when present, are justified by the approximations taken and by the fact that this
 287 analysis considers only single strategies—chosen as the prototype for each drifting group (see Section S2)—
 288 while the invasion graphs in Fig. S4 take the entire drifting group into account.

289

290 **References**

- 291 [1] Fudenberg D, Imhof LA. Imitation processes with small mutations. *J Econ Theory*. 2006;131:251–262.
- 292 [2] Imhof LA, Fudenberg D, Nowak MA. Evolutionary cycles of cooperation and defection. *Proceedings of the National Academy of Sciences of the United States of America*. 2005;102(31):10797–10800.
- 294 [3] Hilbe C, Martinez-Vaquero LA, Chatterjee K, Nowak MA. Memory-n strategies of direct reciprocity. *Proceedings of the National Academy of Sciences*. 2017;114(18):4715–4720.
- 296 [4] Vasconcelos VV, Santos FP, Santos FC, Pacheco JM. Stochastic Dynamics through Hierarchically Embedded Markov Chains. *Phys Rev Lett*. 2017;(118):058301.

- 298 [5] Sigmund K. *The Calculus of Selfishness*. Princeton: Princeton University Press; 2010.
- 299 [6] Hauert C, Michor F, Nowak MA, Doebeli M. Synergy and discounting of cooperation in social dilemmas.
300 *Journal of theoretical biology*. 2006;239(2):195–202.
- 301 [7] Pacheco JM, Santos FC, Souza MO, Skyrms B. Evolutionary dynamics of collective action in N-person stag
302 hunt dilemmas. *Proceedings of the Royal Society of London B: Biological Sciences*. 2009;276(1655):315–321.
- 303 [8] Souza MO, Pacheco JM, Santos FC. Evolution of cooperation under N-person snowdrift games. *J Theor
304 Biol*. 2009;260(4):581–588.
- 305 [9] Pinheiro FL, Vasconcelos VV, Santos FC, Pacheco JM. Evolution of all-or-none strategies in repeated
306 public goods dilemmas. *PLoS computational biology*. 2014;10(11):e1003945.
- 307 [10] Martinez-Vaquero LA, Cuesta JA, Sánchez A. Generosity Pays in the Presence of Direct Reciprocity: A
308 Comprehensive Study of 2×2 Repeated Games. *PLoS ONE*. 2012;7:e35135.
- 309 [11] Nowak MA, Sasaki A, Taylor C, Fudenberg D. Emergence of cooperation and evolutionary stability in
310 finite populations. *Nature*. 2004;428(6983):646.
- 311 [12] Traulsen A, Nowak MA, Pacheco JM. Stochastic dynamics of invasion and fixation. *Phys Rev E*.
312 2006;74:011909.
- 313 [13] Wu B, Gokhale CS, Wang L, Traulsen A. How small are small mutation rates? *Journal of mathematical
314 biology*. 2012;64(5):803–827.
- 315 [14] Imhof LA, Fudenberg D, Nowak MA. Evolutionary cycles of cooperation and defection. *Proc Natl Acad
316 Sci USA*. 2005;102:10797–10800.
- 317 [15] Hong Y. On computing the distribution function for the Poisson binomial distribution. *Computational
318 Statistics & Data Analysis*. 2013;59:41–51.
- 319 [16] Kurokawa S, Ihara Y. Emergence of cooperation in public goods games. *Proceedings of the Royal Society
320 B: Biological Sciences*. 2009;276(1660):1379–1384.

	Ecological conditions G/\tilde{G}	Signalling quorum Q/\tilde{Q}	Memory on cooperation M/\tilde{M}	Number of strategies
B	-	-	-	2
B⁺	a	-	-	2^2
R	-	-	a	2^2
R⁺	a	-	a	2^4
S	s	a	-	2^4
S⁺	s, a	a	-	2^6
S+R	s	a	a	2^6

Table S1. Summary of the combination of mechanisms analysed. For each combination of mechanism exploited, we provide the possible input variables (ecological condition G/\tilde{G} , attainment of the signalling quorum Q/\tilde{Q} and achievement of the cooperation threshold M/\tilde{M}), which determine the possibility to signal (s) and/or to act (a). The total number of resulting strategies for each experimental condition is also shown.

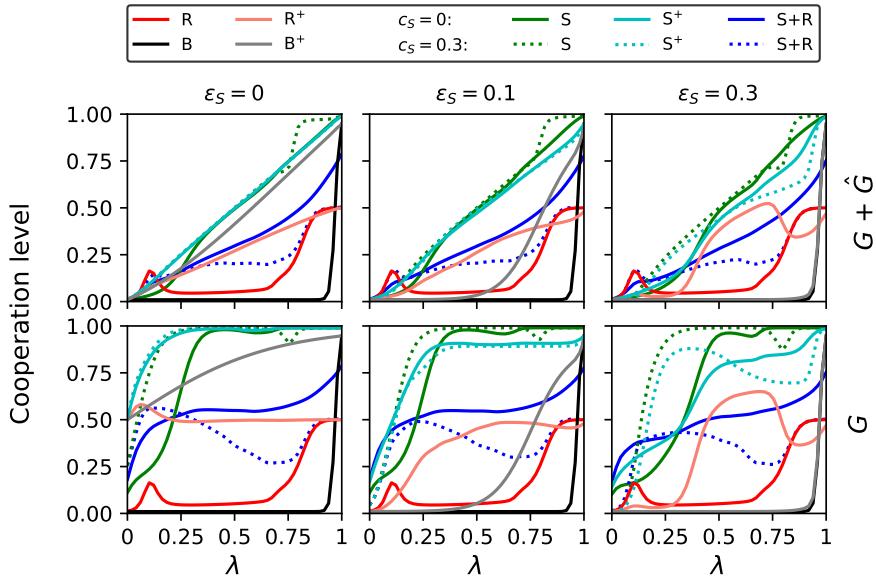


Figure S1. Cooperation level attained under different evolutionary conditions. Similarly to Fig. 1 in the main text, we consider reciprocity (**R**), signalling (**S**), the combination of them (**S+R**), the baseline scenario (**B**), and strategies with the ability to discriminate between G and \tilde{G} (**R⁺**, **S⁺**, and **B⁺**, respectively). Different values of the cost of signalling are considered. The first row displays the level of cooperation attained when both states G and \tilde{G} are considered, and corresponds to Fig. 1 in the main text. The second row shows the level of cooperation when only the G state is considered. Model parameters: $M = 5$, $Q = N/2$, $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

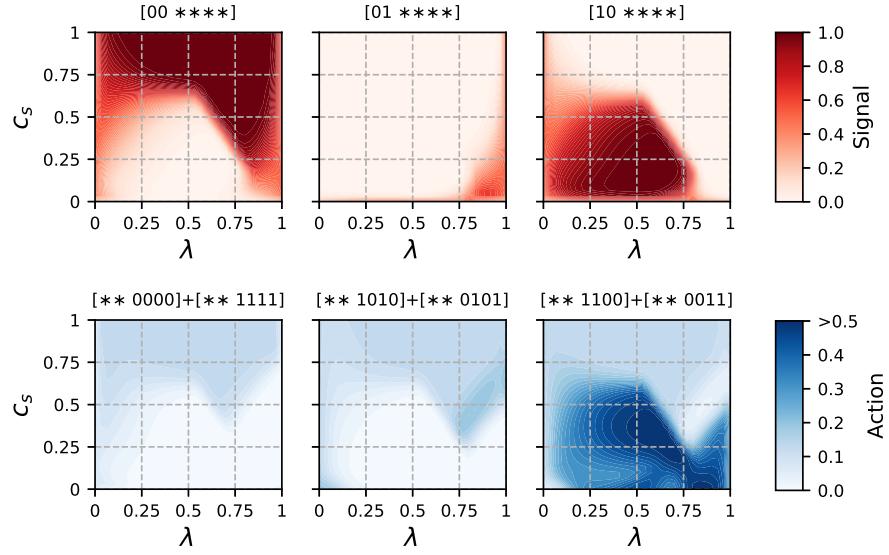


Figure S2. Prevalence of strategies grouped by signalling or acting behaviour. Similarly to Fig. 2 in the main text, the plots show the aggregated probabilities in the stationary distribution of strategies across the $\{\lambda, c_S\}$ parameter space. Here, the behaviour for $M = 7$ is displayed. Signalling strategies (top row) are grouped by the first two bits ($s_G, s_{\tilde{G}}$), ignoring the always-signalling group which has negligible prevalence. Concerning the action part (bottom row), we show groups of strategies that exploit either reciprocity (middle panel) or signalling (right panel), in comparison to strategies that do not use any mechanism (left panel). Model parameters: $Q = N/2$, $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

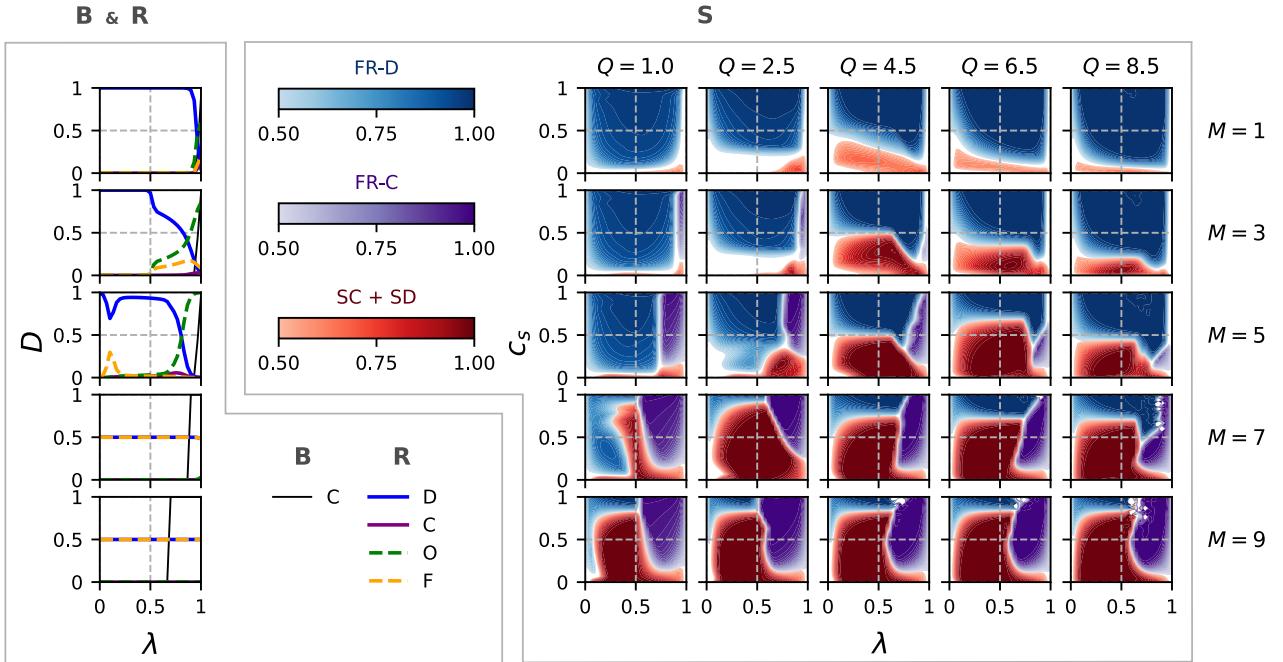


Figure S3. Stationary distribution in the **B, **R** and **S** condition.** The baseline **B** and the reciprocity **R** conditions are displayed in the leftmost column, and only signalling **S** is shown with varying quorum Q in the remaining panels. For **B** and **R**, the column shows the probabilities of all the possible strategies for different thresholds M . The other panels show the stationary distribution of the most successful group of strategies when signalling is the sole mechanism available (condition **S**), and for different values of M and Q . Only probabilities higher than 0.5 have been displayed to facilitate the visualisation in overlapping areas. Model parameters: $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

		$\lambda = 0.2$	$\lambda = 0.5$	$\lambda = 0.8$	
B	D	1.0	D	1.0	
B⁺	(C, D)	0.65	(C, D)	0.82	
	(D, D)	0.2	(D, D)	0.35	
R	D	0.92	D	0.93	
R⁺	(O, D)	0.55			
	(C, D)	0.21	(O, D)	0.83	
	(D, D)	0.21			
$c_S = 0$	S	SC+SD D	0.44 0.54	SC+SD	0.98
	S⁺	(SC+SD, D)	0.60	(SC+SD, D)	0.64
$c_S = 0.3$	S	SC	0.96	SC	1.0
	S⁺	(FR-C, FR-D)	0.92	(FR-C, FR-D)	0.97
				(FR-C, FR-D)	0.98

Table S2. Stationary distribution under every mechanism separately. Stationary distribution of the main strategies or group of strategies that emerge under conditions **B**, **B⁺**, **R**, **R⁺**, **S**, and **S⁺** for different values of λ assuming that there is no error in perceiving the ecological context ($\epsilon_S = 0$). Strategies under **B⁺**, **R⁺**, and **S⁺** are shown as the composition of two strategies between parenthesis; individual chooses the first strategy when under G and the second when under \tilde{G} . Numbers on the right of each strategy indicate their probability in the stationary distribution. Parameters of the model: $M = 5$, $Q = N/2$, $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

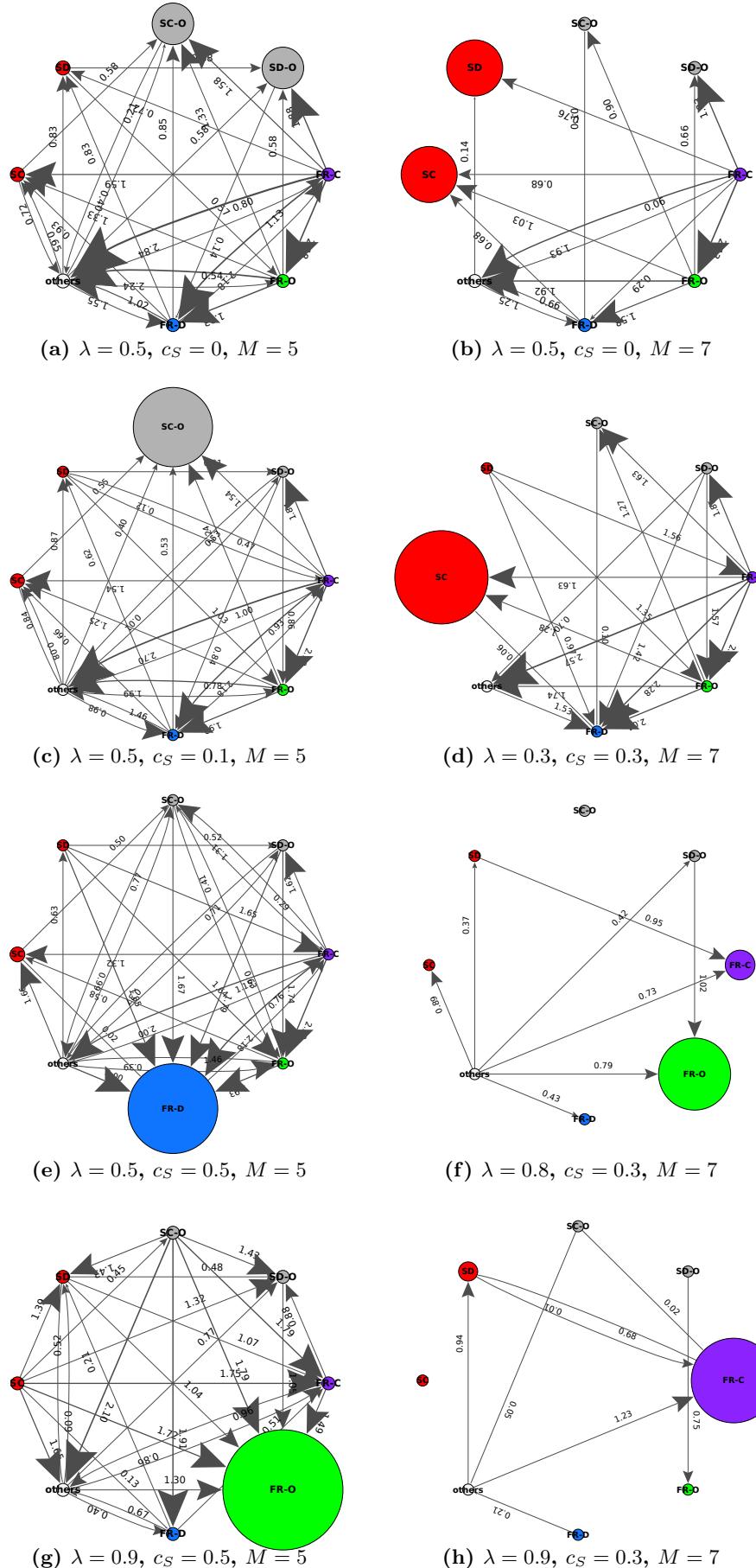


Figure S4. Graphs of invasion among the most representatives groups of strategies. Each panel shows the invasion graph for different combinations of λ , c_S and M . The node size is proportional to probabilities in the stationary distribution. The arrow size and numbers above them correspond to the logarithm of the normalised transition probability among groups of strategies $G(vn\eta)^{-1}$. Parameters of the model: $Q = N/2$, $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

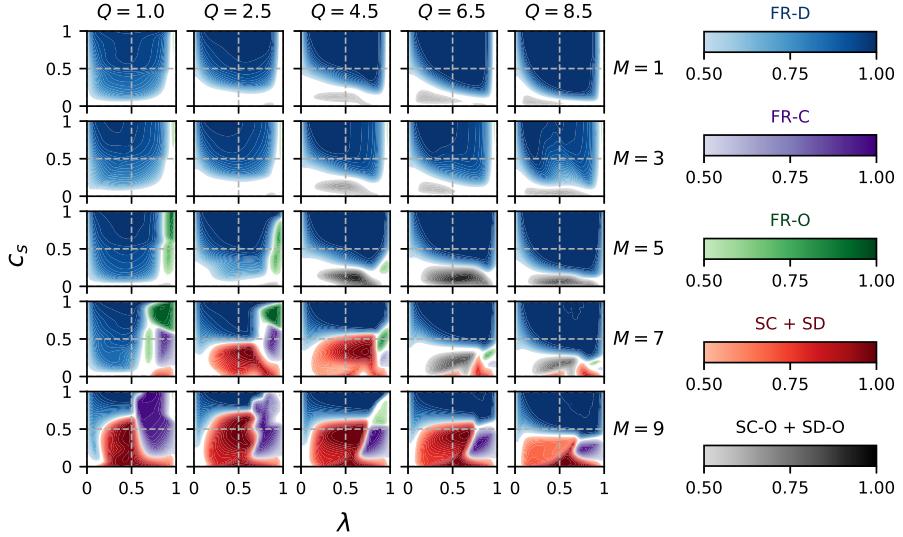


Figure S5. Stationary distribution of the main groups of strategies for $\omega = 0.9$. Note that reducing the number of rounds does not change in general the results. The main difference with respect to Fig. 4 in the main text takes place when Q is high and M intermediate-low. In this case, one can detect the reduction of the success of **SC-O** and **FR-O** strategies for a high cost of signalling c_S . Model parameters: $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

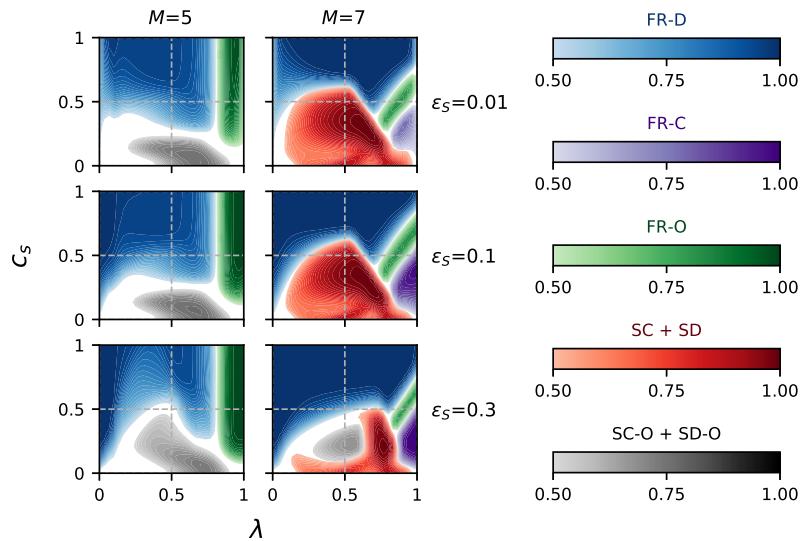


Figure S6. Stationary distribution of the main groups of strategies for different values of ϵ_S . Model parameters: $Q = N/2$, $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

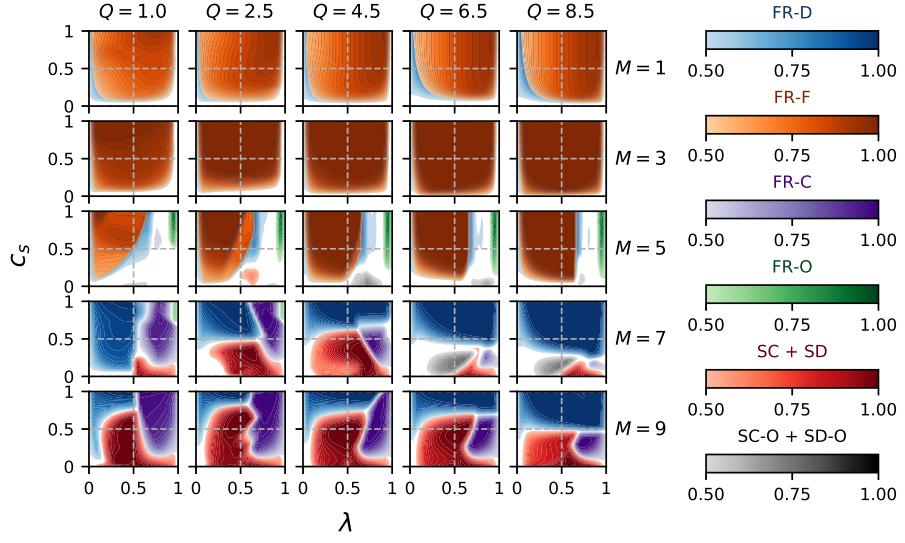


Figure S7. Stationary distribution of the main groups of strategies for the benefit-perceived scenario under no resource. Model parameters: $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

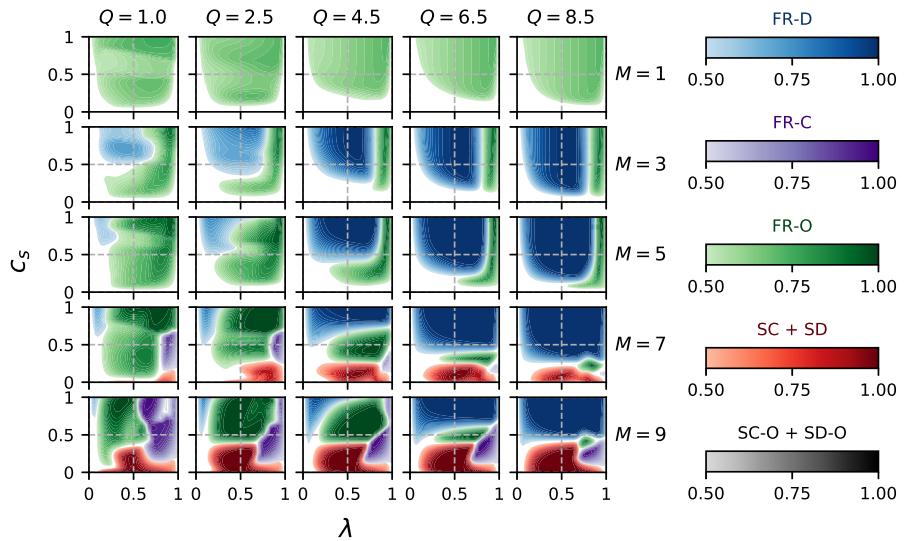


Figure S8. Stationary distribution of the main groups of strategies for the benefit-perceived scenario under abundance. Group of strategies **SC** and **SD** corresponds to [100*11] and [01110*], respectively. Model parameters: $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.

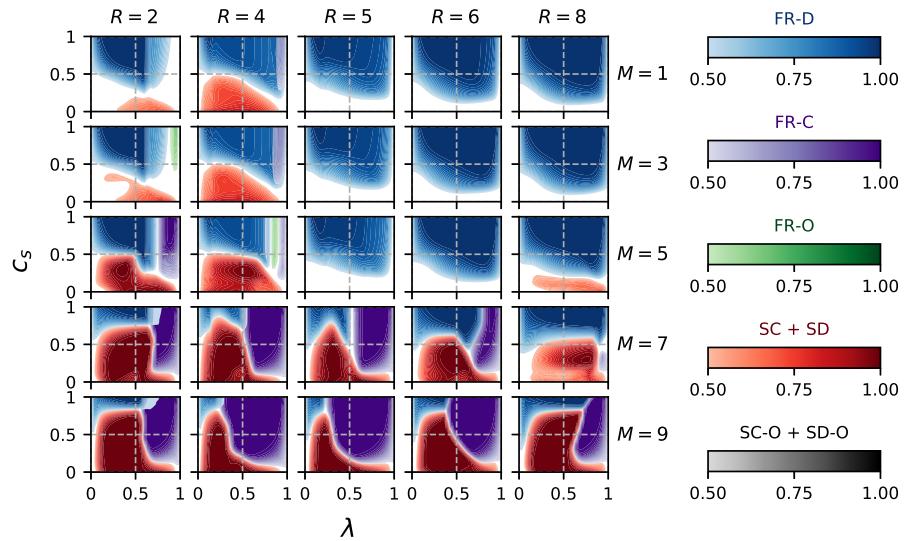


Figure S9. Stationary distribution of the main groups of strategies for the self-aware scenario.
 Group of strategies change as follows: **SC** corresponds to [10 001*] when $R < 5$ and to [10 *011] otherwise; **SD** corresponds to [01 1*00] when $R < 5$, and to [01 11*0] otherwise; **FR-C** corresponds to [00 1***] when $R < 5$, and to [00 11**] otherwise. Model parameters: $Q = N/2$, $\omega = 1$, $\beta = 1$, $r = 10$, $c = 1$, $\epsilon = 0.01$, $N = 9$, and $Z = 100$.