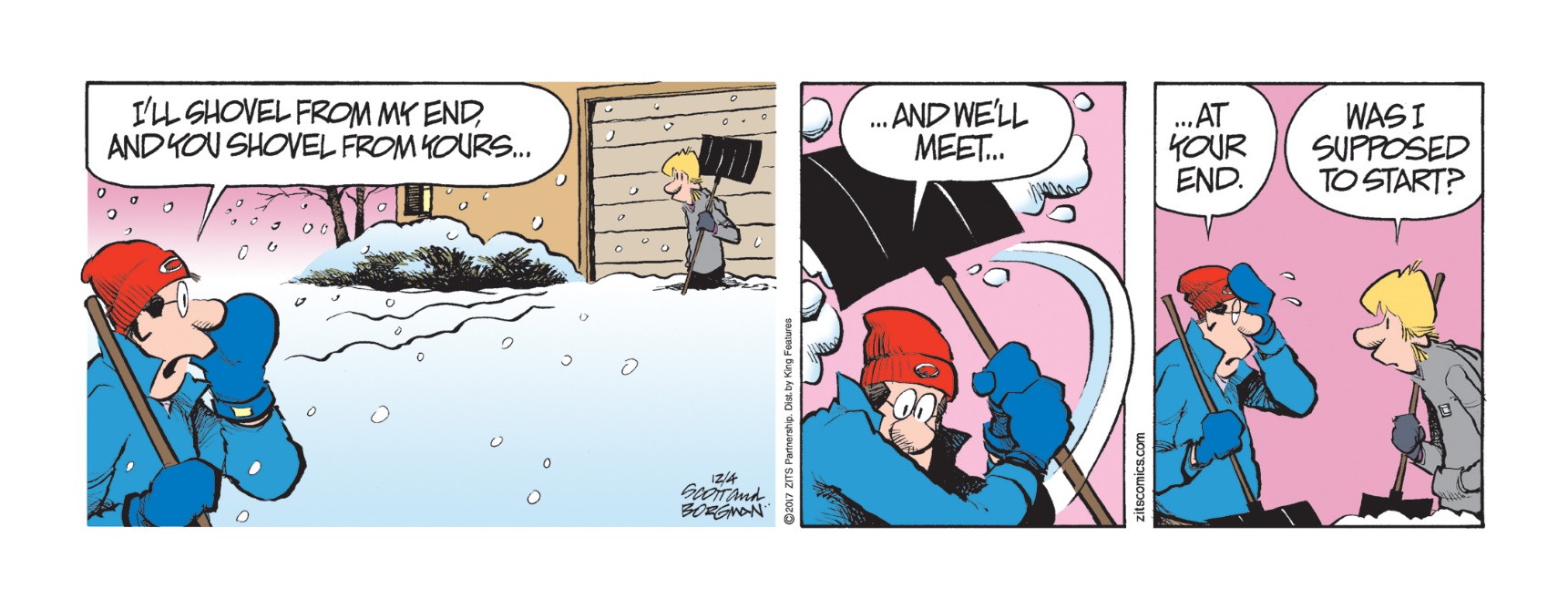
Evolution of cooperative personalities in a cooperation game

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1. Introduction

Recently, empirical research suggests that animals show different personalities within a population, which is defined as different individual behaviour that is consistent over time (e.g. as a juvenile and as an adult) and context (e.g. in interaction with a predator and a potential mate). [1] This is found in the whole animal kingdom in birds, chimpanzees, fish, amphibians [2], spiders [3] and insects [4]. From an adaptive perspective, an infinite plasticity of behaviour would be preferable, since an individual would be able to exhibit optimal behaviour in any kind of situation. Then why is this not observed in the empirical data? Could some poorly understood evolutionary mechanism be at the core of this?

While aggressiveness and responsiveness [5] have been subject to recent research, no models shed light on cooperation as a personality characteristic. It has been suggested that consistent behavioural differences could be the result of social interactions. [6] As seen with aggressiveness, individuals of many different organisms show different behaviour regarding cooperativeness. While cooperation can be seen as an inherited trait, some more properties could be the core of development of personalities, such as responsiveness. The aim of this study is to look at the influence of responsiveness on the development of cooperative behaviour. Do different cooperative personalities evolve to coexist in populations where responsiveness is subject to mutation? What is the consequence of cooperation in a population?

To research these questions, we simulate evolution of cooperation in a snowdrift game. Then we introduce conditional cooperativeness (in the form of responsiveness) to see if this can evolve and if this can cause different cooperative personalities to emerge.

In order to simulate cooperation, a snowdrift game was used. In a snowdrift game, two individuals interact with one another to perform a certain task. When at least one individual decides to cooperate, both individuals gain the benefits of completing the task. However, cooperating does entail a cost. When both individuals cooperate, this cost is shared between them.

1. Baseline model
   1. The snowdrift game

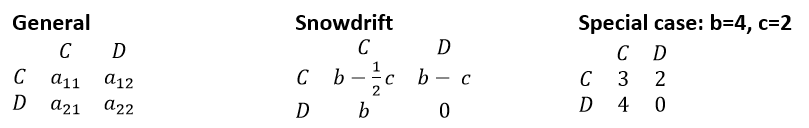


Table 1. Pay-off matrices of snowdrift game.

Figure 1 shows the fitness graph of the snowdrift game. The benefits (b=4) and the costs (c=2) are the same as used in the simulations. On the x-axis the population’s mean tendency to cooperate () is given, whereas the y-axis shows the expected fitness (F). When all individuals in the population defect ( = 0), the best strategy to play is to cooperate. The mean tendency to cooperate will increase as a result of this. When the tendency to cooperate is 1 for every individual in the population, it would be better to defect. This would decrease the mean tendency to cooperate. An evolutionarily stable strategy is predicted at around ( = 0.67) of the population.

Figure 1. Fitness graph of snowdrift game.

F(D)

F(C)

* 1. Set-up of te simulation

A population consists of 1000 individuals, which all have a certain intrinsic tendency to cooperate (P0) between 0 and 1. This trait determines whether the individual cooperates or defects during a given interaction. Each individual has 10 interactions within its lifetime with randomly chosen individuals from the population. The interactions are based on the snowdrift game and the payoffs an individual receives from these 10 interactions are added together. This sum is the individual’s fitness. The fitness values of all individuals in the population are used as the weights for a weighted lottery in order to determine which individuals produce how many offspring for the next generation. During the reproduction, there is a chance (µ) of 0.01 that a mutation occurs. This mutation leads to a small change in the P0 value, taken from a Gaussian distribution with a standard deviation (σ) of 0.01. The model is implemented in C++.

* 1. Evolution in the absence of responsiveness

This model was used as the basis for later developments, but here the aim was mainly to see if the expected equilibrium from the pay-off matrix of the snowdrift game was found.

Figure 2. Left: Mean cooperativeness of three populations with different initial values. Right: Standard deviation of mean cooperativeness of three populations.

Figure 2a shows the mean cooperativeness of three different populations to see if the value of 0.67 which was predicted for our variant of the snowdrift game is reached. The standard deviations show that the variation is quite low, with some larger outbursts, which is due to stochasticity. With so little variation (more than 95% of the data is between 0.67±0.04), it is fair to say that no personalities emerged. The expected cooperativeness equilibrium is indeed found at approximately 0.67.

1. Introducing responsiveness
   1. Including responsiveness in the model

Responsiveness is introduced as another trait value (Pi) which is either 0 or 1. An individual with a Pi of 0 is unresponsive and one with a Pi of 1 is responsive. A responsive individual can observe which strategy its partner used in a previous interaction and respond to that by changing its own strategy. The responsive individual does have to pay a fitness price[[1]](#footnote-1) for this, however. Responsiveness is also affected by mutation; during the reproductive phase, there is a 0.01 chance of mutation (µ) which turns a responsive individual into an unresponsive individual and vice versa.

* 1. Evolution of responsiveness

Figure 3. Left: Mean cooperativeness for unresponsive and responsive individuals and the population mean for three different populations. Right: Fraction responsives in three different populations. Responsiveness could not occur for the first 100,000 generations.

The mean cooperativeness goes to the equilibrium at 2/3 cooperativeness in all three populations before the responsiveness can occur. Then, responsiveness emerges very quickly in all three cases; in the one with low initial cooperativeness, the responsives go to an equilibrium immediately, but the ones with high and medium initial cooperativeness first reach a high fraction of responsives, before reaching the same equilibrium of around 55% responsives. At the moment the responsiveness emerges the unresponsive individuals reach an equilibrium where they always defect, while the responsives have a high cooperativeness. The high initial cooperativeness case shows an intermediate state, where unresponsives keep a high responsiveness for a bit longer before going to almost no cooperation. All the cases show a dip in the average of the population as responsiveness emerges.

Thus, responsiveness is able to emerge from a totally unresponsive population. Unresponsives always seem to choose defect over cooperation.

* 1. Effect of price of the evolution of responsivenss

Figure 4. Left: Mean cooperativeness of responsive and unresponsive individuals and the population average for a population with medium initial cooperativeness. Right: Fraction responsives in a population with medium initial cooperativeness.

The graph on the left shows the average cooperativeness, which is almost the same as the cooperativeness of the unresponsives, because almost no responsives are present. This is seen in the graph on the right. The price is too high for responsiveness to maintain a substantial part of the population. Now, only due to stochasticity very low numbers of responsives are present in the population.

*Calculating the threshold price*

According to Wolf et al. [7], the fitness price an individual pays for obtaining information has to be sufficiently low in order for responsiveness to emerge in the population. The exact value can be calculated by the following formula.

The different α values are the values from the payoff matrix, see table 1. This simplifies the formula to the following.

In the simulation with a price of 0.0, we found that the standard deviation was approximately 0.02. This leads to the assumption that the price can be no larger than 0.0012 if responsiveness is to emerge.

First, a price of 0.001 was tested to see if responsiveness could occur.

*Price for responsiveness: 0.001*

Figure 5. Left: Mean cooperativeness of responsive and unresponsive individuals and the population average for a population with medium initial cooperativeness. Right: Fraction responsives in a population with medium initial cooperativeness.

Responsiveness emerges very quickly, within 100 generations. Next, several other simulations with different prices were implemented, ranging from 0.005 till 0.5.

*Price for responsiveness: 0.5*

Figure 6. Left: Mean cooperativeness of responsive and unresponsive individuals and the population average for a population with low initial cooperativeness. Right: Fraction responsives in a population with low initial cooperativeness.

One of the three populations (different initial cooperativeness) which were tested at first, showed an emerge of responsiveness. Upon these findings, ten additional simulations were performed under the same circumstances. See extended data 5. Out of the ten simulations, eight showed an emergence of responsiveness. The right shows a responsiveness fraction of 20 – 25%. This seems to go directly against the previously shown equations of the maximum price for responsiveness.

1. Responsiveness as a continuous trait

Instead of individuals always being responsive or always being unresponsive, responsiveness was changed to be anything between 0 and 1. This way the model would become more realistic, because responsiveness is sort of like a spectrum: some individuals respond more than others, but don’t always respond. From the personality’s perspective, a more static behaviour is expected, but this can also be slightly plastic. Therefore, it is more logical to have a slight change in the responsiveness instead of a choice between responsive and unresponsive.

*Price for responsiveness: 0.0*

Figure 7. Left: Mean cooperativeness for unresponsive and responsive individuals and the population mean for three different populations. Right: Fraction responsives in three different populations. Responsiveness could not occur for the first 100,000 generations.

Responsiveness emerges and reaches the same equilibrium as with the Boolean responsiveness. This can be seen in the right graphs. Thus, responsiveness emerges when it is a continuous trait, however it takes longer to reach this equilibrium. The unresponsive individuals choose defect over cooperation in the end, as seen before, while the responsive ones go to high cooperation levels.

*Price for responsiveness: 0.3*

Figure 8. Left: Mean cooperativeness of responsive and unresponsive individuals and the population average for a population with medium initial cooperativeness. Right: Fraction responsives in a population with medium initial cooperativeness.

Introducing a higher price shows that the expected value of a maximum price also doesn’t apply for continuous responsiveness. The right graph shows that after about 250,000 generations responsiveness occurs in the population. The variation before responsiveness occurs, seems lower than in the case with no price, see figure 7 high initial conditions.

*Price for responsiveness: 0.5*

Figure 9. Left: Mean cooperativeness of responsive and unresponsive individuals and the population average for a population with high initial cooperativeness. Right: Fraction responsives in a population with high initial cooperativeness.

This simulation was performed with three different initial conditions, where none showed an emergence of responsiveness. Above shows only the high initial conditions, in which case the mean cooperativeness goes to an expected 2/3 cooperation in absence of a high number of responsive individuals.

1. Conclusion and discussion

It seems that by introducing responsiveness to a population, a clear difference in strategy is sparked as two obvious personalities emerge. Responsive individuals tend to go for cooperation, while the unresponsive individuals end up defecting most of the time. This is probably due to a discrepancy in the pay-off matrix of the game dynamics of the snowdrift game. Between α12 (b – c) and α21 (b) for an unresponsive individual interacting with a responsive individual, α21 gives a higher fitness than α12, and therefore defecting is the strategy which will be more successful. As a result of this, unresponsive individuals in a highly responsive populations tend to defect after reaching equilibrium. See figure 3, high initial responsiveness. Due to the emergence of responsiveness, the average cooperativeness of the population decreases and the number of unresponsive individuals becomes very low. Only until the unresponsive individuals change their strategy to defect more often, do they regain a substantial part of the population.

The equation stated by Wolf et al. was used to calculate the max price for responsiveness under certain variation in the population. Several different prices for responsiveness were investigated, when it was found that even with a price as high as 0.5, responsiveness came about in the population, see extended data 6. The next step was introducing responsiveness as a continuous trait. The data was more apt of stochasticity when a certain level of responsiveness had been reached before the responsiveness could obtain an equilibrium. The equation also didn’t seem to apply here, because even with a price of 0.3 responsiveness could still occur in the population.

A next step would be to let the strategy of responsive individuals evolve. Right now, the responsive individuals would always choose the opposite strategy of that of the opponent. It would be interesting to see where the population dynamics go, when individuals’ responses are free to evolve.

In this model, only the game dynamics of a snowdrift game were presented, while it would give a much clearer image of cooperation if other sorts of game were introduced as well. One direct suggestion would be to look at a snowdrift game with a more symmetric fitness matrix to see if different equilibria can come about.

One could also imagine a population with several meta-populations, who all have a certain exchange of individuals. The interesting thing would be to see if big differences evolve next to each other and if they can trigger responsiveness for example in other non-responsive meta-populations.

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**Appendix**

1. Model in the absence of responsiveness

Data of the model in which an individual’s strategy is either always cooperate or always defect. As seen in the graph below, two thirds of the population will cooperate, as is expected.

*Above shows the development of the mean fraction of cooperatives in a population of three population with different initial conditions. The blue points represent the population with 95% cooperatives, grey the one with 67% and orange the one with 5%.*

1. Detailed depiction of the implementation of responsiveness

|  |  |  |
| --- | --- | --- |
| Partner  Focal | Responsive | Unresponsive |
| Responsive | Cf = 1 – Pmean  Df = Pmean  Cp = 1 – Pmean  Dp = Pmean | Cf = 1 – P0(p)  Df = P0(p)  Cp = P0(p)  Dp = 1 – P0(p) |
| Unresponsive | Cf = P0(f)  Df = 1 – P0(f)  Cp = 1 – P0(f)  Dp = P0(f) | Cf = P0(f)  Df = 1 – P0(f)  Cp = P0(p)  Dp = 1 – P0(p) |

*Table 3. Chances a focal individual and its partner receive a certain fitness based on the different strategies played in different scenario’s. The* f *means focal,* p *means partner,* D *is to defect and* C *is to cooperate.*

Above, four scenarios in model 1.1 are laid out an individual can be responsive and unresponsive and can interact with a responsive and unresponsive individual. It shows the chances an individual which is either responsive or not responsive will cooperate or defect when interacting with a responsive or not responsive individual. Cf = chance focal individuals cooperate, Df­ = chance focal individual defects, Cp and Dp­ are the same but than for the partner. Pmean is the average cooperativeness in the last generation, where P0 is an individual’s intrinsic cooperativeness.

1. Quantifying the effects of genetic drift and mutation

This is a control model to see if an equilibrium is found in the responsiveness. Therefore, no selection is made for the next generation based upon fitness. Instead of a weighted lottery, a uniform distribution is used for determining the next generation.

Three replica populations are run in a simulation over 200,000 generations. The last part is the most useful, due to the absence of initialisation effects (which come about when there is not much variation just yet), therefore only the last 500 generations are shown.

As no selection is acting on the populations, the fraction responsive individuals in the population goes to random oscillations around 0.5 as is expected.

*Above shows the fraction of the populations which is responsive. The mean cooperativeness of two of the three replicas is also shown. Blue is the average of the population, grey shows the average of the unresponsive individuals and orange that of the responsive individuals.*

Two different outcomes of drift are shown in the graphs above, where drift pushes the two different population to different average cooperativeness. Interestingly, the unresponsive individuals always seem to have little variation, at least less than the responsive individuals. This makes sense when responsive individuals randomly encounter unresponsive and responsive individuals and are therefore more influenced by chance, while unresponsive stick to their intrinsic cooperativeness.

*Above shows the standard deviation of the unresponsive individuals of three populations.*

Although, more variation is perhaps expected in the three populations shown above, the small standard deviation is due to the small mutation rate (= 0.01). On top of that, these graphs show only the last 500 generation, more variation could be possible over the whole course.

The null model of model 1.1 shows that without selection on responsiveness an equilibrium of 0.5 is reached with high fluctuations. Generic drift takes over the main strategies for the populations. This shows the robustness of the model 1.1.

1. Effect of a high price on the evolution of responsiveness

*Below the data for the high price for responsiveness is shown for high and low initial conditions.*

Both the graphs for high initial cooperativeness and the graphs for low initial cooperativeness show extremely low responsiveness and therefore a similar average to no responsiveness (first 100,000 generations).

1. Responsiveness with a price of 0.5 extra data

Two of the 10 extra simulations run for responsiveness price of 0.5 with several different initial conditions. The simulations first run 100,000 generation to get to equilibrium as seen before. Then responsiveness is introduced by mutations. In 8 of the 10 simulations, responsiveness came up. The lower fraction of responsive individuals is in line with the higher price for responsiveness.

1. Responsiveness as continuous trait extra data

*Price for responsiveness: 0.3*

Above shows in high initial cooperativeness an emergence of responsiveness, while in the low initial cooperativeness no responsiveness could occur.

*Price for responsiveness: 0.5*

The above graphs show no emerge of responsiveness.

1. Different benefits and costs in snowdrift game

*Fitness graph of snowdrift game with benefits = 5, costs = 4.*

To see if the dynamics of a snowdrift game change when benefits and costs are different, the equilibrium was changed to 1/3. This was done by calculating the new benefits and costs, 5 and 4 respectively.

*The left shows the mean cooperativeness for the average of the population, responsives and unresponsives. The right is the fraction of responsives in the population.*

It can be seen that the equilibrium is lower than expected, but that the dynamics qualitatively don’t change. Still the unresponsives defect resulting in the fact that the responsives cooperate more. Therefore, changing the benefits and costs doesn’t change the game dynamics qualitatively.

1. Since this price is subtracted from an individual’s fitness, it is possible an individual ends up with a negative fitness. To prevent this from happening, every individual receives a baseline fitness of 11 times the price. [↑](#footnote-ref-1)