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Male and female robots

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Abstract

We evolve a population of male and female robots which to remain alive must eat the food contained in their environment and to reproduce must mate with a robot of the opposite sex. The only difference between male and female robots is that after mating males can mate again (reproductively) while females have a fixed period during which they are nonreproductive. The results show that males have a greater variance in reproductive success compared to females and they tend to be always very active looking for the “scarce resource” constituted by reproductive females and eating any food they are able to find while they are looking for reproductive females. Reproductive females are less active than males and they adopt the reproductive strategy of waiting for males to find and mate with them. On the contrary, nonreproductive females are as active as males but they look for food and are not interested in anything else. We also find a number of differences between males and females in their preferences for different types of food and in offspring care if males do not have parental certainty.

Key words: robots, male and female, sexual differences

1. Male and female

Most animals have two sexes, male and female, and to reproduce an individual must mate with an individual of the opposite sex. Mating has different consequences for males and females. After mating, males can immediately reproductively mate with another female, while after successful mating females have a period in which they are not reproductive due to pregnancy, hormonal changes, lactation, and other factors. The objective of the present study is to explore the behavioural consequences of this single difference between males and females by constructing male and female robots. The general idea behind the research is that to understand X one potentially useful approach is to reproduce X in an artificial system. If the artificial system behaves like X, then we can suppose that the theory or model which has been used to construct the artificial system may help us to understand and explain X. But our robots are not constructed by us in the sense that they are programmed by us. Instead, we let a population of male and female robots live and reproduce in an artificial environment in a succession of generations and we determine if and how the evolved behaviour of male robots is different from the behaviour of female robots.

Our robots are very simplified with respect to real animals and they are not intended to reproduce any specific animal species. There is a very rich literature on sexual differences in behaviour in both nonhuman and human animals (e.g., Kimura, 2000; Baron-Cohen, 2003; Becker et al., 2008) and some of this literature looks at these differences in an evolutionary perspective (Low, 2000; for an evolutionary feminist perspective on sexual differences, cf. Gowaty, 1997). However, since the nature of sexual differences depends on the particular adaptive pattern of the different species we cannot directly compare the behaviour of our robots with the behaviour of any existing animal. This notwithstanding, we hope our robots will help us to better understand the sexual differences observed in the behaviour of real animals.

One difference which it is claimed to exist between males and females in many animal species is that males are more active than females. This raises a general question. Discussing differences between males and females (especially, men and women) is charged with ideological and political issues, and the three authors of this research (all men) are not immune from these issues. Being active tends to be considered as “better” than being passive, and this may lead to a stereotypical view of sex roles which does not necessarily corresponds to reality (Green and Madjian, 2011). We think robots can be useful from this point of view because when one constructs robots one has to make explicit and specify in detail all of one’s assumptions and everyone can see what are the behaviours which derive from these assumptions, whether one likes these behaviours or not. As will be shown, we find a number of behavioural differences between our male and female robots and one of these differences is that female robots, when they are reproductive, tend to be less active than male robots, although this is not true when female mate successfully and they enter their nonreproductive period. We agree that the idea of “active males” vs “reactive females” can be a stereotype that we must guard ourselves from. But, as we will see, we define “activity” in purely operational terms so that it can be objectively measured. However, one has to consider that our robots do not resemble any particular species of real animals and they are hugely simplified with respect to any real animal. This means that our results may apply to some species but not to others and that “activity” in real animals may be influenced by other factors which are ignored in our robots. However, our robots can point out to some of the factors that may influence “activity” in sexually distinct real animals.

There is not much work on sexual differences in robots and, more generally, in computational models of the behaviour of organisms. In research using genetic algorithms, “offspring” can inherit a genotype which is a recombination of parts of the genotypes of two different individuals (Goldberg, 1989; Holland, 1998; Mitchell, 1998), but the two “parents” are not sexually different

individuals. There is a very interesting line of research on the exchange of communicative signals between artificial males and females for purposes of sexual selection but in this line of research the researcher already assumes that the female is the sender of signals and the male respond to these signals by approaching the female for mating (Werner and Dyer, 1992) or, vice versa, the male emits “songs” in order to be selected for reproduction by a female (Werner and Todd, 1997). On the contrary, we do not assume any a priori behavioural difference between our male and female robots but only a difference in the physical consequences of mating, and we want to see if and which behavioural differences emerge from this single biological difference. Another interesting direction of research has been concerned with strategies of mate choice in abstract artificial organisms (Todd, 1997) but in this research one assumes that the artificial organisms are sexually different without specifying in what they are different. Finally, robots that have the external appearance of men or women are constructed to study how human beings react to them, for both purely scientific goals (Crowell, Scheutz, Schermerhorn, and Villano, X; Patricelli, Uy, Walsh, and Borgia, 2002) or for practical applications in human-robot interaction, but although these robots look like men or women they are not functionally males or females.

Our goal in the present research is to find out if male and female (simulated) robots behave differently, and what are these differences in behaviour, by only assuming that, after successfully mating, for a fixed period of time a female robot cannot successfully mate again, while this is not true for male robots. In the next Section we will describe our robots, the environment in which they live, and the “brain” that controls their behaviour.

2. An evolving population of male and female robots

Our robots are simulated Khepera robots (Mondada, Franzi and Guignard, 1999; Nolfi and Gigliotta, 2010). Khepera robots have a circular body with a radius of 35 pixels, visual sensors with a restricted visual field, and two wheels that allow the robots to move in the environment^[F1]. A group of 100 robots live in an environment which is a square of 7000x7000 pixels closed by a wall and containing 70 randomly distributed food tokens. The robots’ body contains an energy store whose level can go from 1 to 0, where 1 means that the energy store is completely full and 0 that it is completely empty. At each time step the energy contained in the bodily store is reduced by 0.001 units to keep the robot alive and, if it reaches the 0 level, the robot dies^[F2]. (The value of this and other parameters are arbitrary and they have been selected to insure that our robots live long enough to exhibit interesting behaviours.) When a robot touches the environment’s wall, it bounces back in a randomly chosen direction. When it touches a food token, the robot automatically eats the food token: the food token disappears and a quantity of 0.5 is added to the robot’s energy store. Hence, eating a single food token guarantees survival for 500 time steps^[F3]. Notice however that, since a robot’s energy store can contain a maximum quantity of 1, when the store is full the energy extracted from food is lost. Also notice that when a food token is eaten a new food token appears in a randomly selected location of the environment so that the total number of food tokens is always 70. A robot can live a maximum of 15000 time steps but, as we have said, the robot can die at any time if its energy store reaches the 0 level.

However, remaining alive is not sufficient to leave one’s genes to the next generation. Half robots are males and half are females and, to reproduce, a robot must mate with a robot of the opposite sex, where mating occurs when two robots of opposite sex touch each other. Therefore, to leave its genes to the next generation a robot must be able to divide appropriately its time between finding food and mating. After a female has mated with a male, the female becomes nonreproductive for 1500 time steps, which means that, when mating occurs between a male and a nonreproductive female, no offspring are generated.

At the end of their life, the 50 male robots are ranked in terms of the number of (reproductive) mating events of each robot and the 10 highest ranking robots each generate 5 male offspring which inherit the genotype of their father. The same happens for the female robots, with the 10 best female robots each generating 5 female offspring. The new 50 male and 50 female robots constitute the next generation of robots. This is continued for 1000 generations and is replicated 10 times starting from different randomly generated genotypes and random initial locations of the robots and food tokens in the environment.

Male and female robots have bodies of different colours. Male robots are blue, reproductive female robots are pink, and nonreproductive female robots are red, and when a robot perceives another robot, it can recognize if it is a male, a reproductive female, or a nonreproductive female, based on their colour. The food tokens can also be recognized because they are green.

The robots' behaviour is controlled by a neural network with visual units encoding what currently is within the robot's visual field and motor units encoding the speed of the robots' two wheels and therefore the robots' displacements in the environment. The connection weights and biases of the neural networks of the initial population of robots are randomly generated in the interval between +5 and -5_[f4] and therefore these robots tend to be able neither to approach and eat the food tokens nor to approach and mate with the robots of the opposite sex. The robots that have more successful mating events leave more offspring to the next generation, where an offspring is a robot which inherits the connection weights and biases of its parents (genotype), with each weight or bias having a probability of 2% of being mutated _[f5](randomly reassigned_[f6]). The selective reproduction of the best robots and the constant addition of random mutations to their neural networks have the consequence that after a certain number of generations the robots are quite good at finding both food and mating partners.

The neural network that controls the robots' behaviour has a total of 10 input units connected to 5 internal units which in turn send their connections to 2 motor units (Figure 1). Of the 10 input units 8 are visual input units, 4 encoding the presence and position of, respectively, male robots, reproductive female robots, nonreproductive female robots, and food tokens on the left side of the robot's visual field, and 4 on the right visual field. The remaining 2 input units are bodily input units. One encodes the current level of the robot's energy (hunger) and the other one, which exists only in the neural network of female robots, encodes the current state of the female robot's body, with a value of 0 indicating that the robot is currently reproductive and a value of 1 that it is nonreproductive. Hence, females know when they are reproductive or nonreproductive, and this is the neural consequence of having different bodies. The 2 motor units encode the speed of the two wheels that allow the robot to move in the environment_[f7].

Figure 1. The neural network that controls the behaviour of the robots. Visual input originates in the external environment. Hunger and female reproductive state are inputs originating within the robot's body. The bodily input that signals the current reproductive/nonreproductive state of the robot exists only for female robots.

3. Results

In this Section we describe the observed differences in the evolved behaviour of male and female robots.

3.1 Differences in reproductive variance

One difference between male and female robots concerns variance in reproductive success, that is, in the number of offspring generated by each robot. Figure 2 shows how the average number of successful mating events increases across the 1000 generations of robots. By necessity, this number is the same for male and female robots, and at the end of the simulation the average robot has about 6 successful mating events during its life. However, if we look at the best male robot and the best female robot, we find that the best male robot has a greater number of successful mating events (around 15) than the best female robot (around 9-10).

Figure 2. Average number of successful mating events and number of successful mating event for the best male and the best female across 1000 generations (average of 10 replications of the simulation)

To have offspring our robots have to eat because if they do not eat they die and cannot mate. The increase in the number of successful mating events across the 1000 generations implies that our robots evolve both an ability to mate successfully and an ability to eat and therefore to survive. However, these are separate abilities. Two individuals may have the same number of successful mating events but one individual may be very good at eating and therefore at living a long life but not particularly good at mating, while the other individual may not be so good at eating and therefore it may die before maximum living age but it may be very good at mating during its shorter life. How males and females compare in terms of the two abilities? The answer is that while the best male and female robots have the same life length and after 500 generation they are both able to reach the maximum living limit (15000 time units), the average male lives longer than the average female (Figure 3). In fact, on average males live between 11000 and 12000 time steps while females live between 10000 and 11000 time steps.

Figure 3. Life length of best and average male robots and best and average female robots.

Furthermore, if we count the number of food tokens eaten by males and females during their life, we find that both the best and the average males eat more than the best and average females, respectively (Figure 4).

Figure 4. Number of food tokens eaten by best and average males and best and average females across 1000 generations.

In our robots length of life and number of food tokens eaten are correlated but not perfectly correlated. In fact, while the best females have the same life length of the best males, they eat somewhat fewer food tokens than the best males. This seems to imply that the best females are able to eat more efficiently than the best males in that they succeed in living as long as the best males while eating somewhat fewer food tokens than the best males. It is also worth noting that on average males eat more and live longer than females since the very first generations. This can be explained by the fact that females have to cope with a richer input, which includes information about their current reproductive state, and this may create a partial interference with the task of finding food, resulting in a poorer performance.

Another difference between males and females concerns how length of life and mating success are related in males and females. In our robots length of life is determined by eating. However, if we ask how length of life is related to mating success we find that in females mating success is strongly correlated with mating success while this is not true for males. We have taken the 100 robots of the last generation for all the 10 replications of the simulation (50x10=500 males plus 50x10=500 females), we have ranked separately males and females in terms of number of successful mating events, and we have determined the life length of each robot. The results are shown in Figure 5.

Figure 5. How ranking in reproductive success and length of life are related in males (a) and females (b).

As one can see from Figure 5, while females that have more successful mating events tend to be those which live longer, this is not true for males. There are males that have a short life but more reproductive success than other males which live longer. This seems to imply two different adaptive strategies in males and females. Remember that while females can have a maximum of 10 successful mating events during their entire life (assuming that they reach the maximum life length of 15000 time steps), males do not have this limit since, theoretically, they can have a successful mating event at each time step. Hence males' reproductive success is measured by their ability to find reproductive females to mate with rather than by their ability to find food. In contrast, females do not have to look for males because it is males that will look for them, and their only problem is to eat and live a long life so that they can express their maximum reproductive potential (10 reproductive matings). It is interesting, however, that since the reproductive strategy of males is based on a greater mobility in the environment in search for reproductive females, this greater mobility causes males to encounter and eat more food and therefore, on average, to live longer than females. (In our simulations males eat a lot because they move a lot. But consider that for our robots there are no costs associated with movement while this is not true for real animals.)

In Section 3.2 we look more closely at the behaviour of the robots in their natural environment while in Section 3.3 we examine the behaviour of male and female robots in a more controlled experimental setting.

3.2 The behaviour of the robots in their natural environment

We have said that males and females behave differently in that their behaviour produces different results in terms of number of successful mating events, number of food tokens eaten, and length of life. But we can also examine males' and females' behaviour directly and see if they behave differently. What we find is that not only males behave differently from females but females behave differently when they are reproductive and when they are nonreproductive.

Males tend to move more and to explore more of the environment than females but this difference is especially significant only with respect to reproductive females, not to nonreproductive females. Males tend to always be very active and they always look for something (food or reproductive females). On the other hand, when females are reproductive they do not move much, although when they become nonreproductive, they are almost as mobile and explorative as male robots. Apparently, while the mating strategy of males is to move in search of reproductive females, the mating strategy of reproductive females is to stay where they are and to wait for males to reach and mate with them. Nonreproductive females do not have a problem of mating and therefore they can freely move around searching for food. This has consequences for eating and surviving. Although male robots appear to be more interested in reproductive females than in food (see next Section), they eat more, and on average live longer, than female robots.

To have more precise and quantitative data on the behaviour of our robots in their environment, we have devised two measures of mobility/exploration. We have divided the entire environment into 10000 square zones of 70x70 pixels each and we have counted the number of different zones visited by males, reproductive females, and nonreproductive females during a period of 200 successive time steps. The initial position of the robot was random and the test was repeated 50 times. The results show that males visit more zones of the environment compared to females (Figure 6a).

Figure 6. (a) Number of different environmental zones visited by males, reproductive females, and nonreproductive females. (b) Difference between the activation levels of the two motor units (speed of the two wheels) for males, reproductive females, and nonreproductive females. The difference is computed according to the formula $D = (m_1 + m_2) \sqrt{m_1 m_2}$.

Our second measure of mobility/exploration is based on the speed of the two wheels of the robots. If the two wheels have more or less the same speed, the robot moves ahead and explored other parts of the environment, while if there is a large difference between the speeds of the two wheels, the robot is moving in circles and is not exploring very much of the environment. Since the speed of the two wheels is determined by the activation level of the two motor units of the robots' neural network, we have measured the difference between the activation level of the two motor units in a succession of 15000 time steps for 10 trials for males, reproductive females, and nonreproductive females, and we have found that males and nonreproductive females tend to have similar activation levels in their two motor output units while in reproductive females the two units tend to have different activation levels (Figure 6b) This confirms that males and nonreproductive females move more and explore more of the environment than reproductive females (although with different purposes because males look for reproductive females while nonreproductive females look for food). Figure 7 shows an example of the path followed by a male during 1900 time steps, by a nonreproductive female during 950 time steps, and by the same female when she becomes reproductive during a further period of 950 time steps.

Figure 7. Path followed by a male during 1900 time steps, by a nonreproductive female during 950 time steps, and by the same female when she becomes reproductive during a further period of 950 time steps.

3.3 The behaviour of the robots in the experimental laboratory

In addition to looking at the robots' behaviour in their natural environment we have studied their behaviour in a controlled experimental setting. An individual "subject" robot is placed in an "experimental laboratory" and is given a choice between two different items. The experimental laboratory is a walled environment of 1600x1600 pixels and each robot is placed at the centre of the laboratory and is presented with two items located at the same distance from the robot, one to the left and the other to the right but both within the visual field of the robot. Each trial is repeated twice by changing the right/left position of the two items (although we were not interested in examining if different robots behave differently as a function of the left/right position of the two items). The two items are all possible pairs made up of one male, one reproductive female, one nonreproductive female, and one food token, with the only restriction that the two items never belong to the same category. While the robot which is the experimental subject is free to move, the robots to which the experimental subject is exposed and, of course, the food token, do not move. Furthermore, we repeat each trial by manipulating the level of energy in the robot's body: from level 1 (full store: not hungry) to 0.75 to 0.50 to 0.25 (almost empty: very hungry). Each trial lasts for 5000 time steps but a trial is terminated if the robot touches the laboratory wall. There are three possible outcomes for each trial: the robot reaches one item, the robot reaches the other item, or it does not reach either item (because the robot touches the wall or the trial is terminated). The results for each of the three categories of robots, males, reproductive females, and nonreproductive females, are the following.

Males which have to choose between a reproductive female and food clearly prefer the reproductive female (Figure 8a).

Figure 8. Males' preferences in the laboratory experiment. Males have to choose between (a) food and reproductive female; (b) reproductive and nonreproductive female (c) food and nonreproductive female.

An even stronger preference for reproductive females is manifested by males when they have to choose between a reproductive female and a nonreproductive female (Figure 8b) or between a reproductive female and a male (data not shown). The situation is reversed when a male has to choose between food and a nonreproductive female (Figure 8c) or another male (data not shown): the male almost always chooses food.

In all cases what characterizes males is that they are very fast in their behaviour and they rarely appear undecided, i.e., the trial terminates without them having reached one of the two items between which they have to choose.

In contrast to males, reproductive females strongly prefer food to males (Figure 9a).

Figure 9. Reproductive females' preferences. Reproductive females have to choose between (a) food and males; (b) male and reproductive female; (c) reproductive and nonreproductive female.

What is even more interesting is that when they have to choose between a male and a reproductive female, reproductive females prefer the male just a little bit more than the reproductive female (Figure 9b). In both cases, and especially in the second one, reproductive females are very hesitant and slow in their behaviour. Another interesting finding is that when reproductive females have to decide between a reproductive and a nonreproductive female, they prefer the reproductive female to the nonreproductive female (Figure 9c), although in this case too they manifest a great indecision and a tendency not to move much. This seems to imply a strategy to go or stay near other reproductive females in order to increase the probability to attract males.

On the other hand, when they become nonreproductive females prefer food to everything else (Figure 10b and 10c) and what characterizes their behaviour is that, in contrast with when they are reproductive, they, like males, are fast and very decided. On the other hand, when food is not one of the two choices, nonreproductive females are not interested in choosing and they tend to go to neither of the two presented items (which are both robots) (Figure 10a).

Figure 10. Nonreproductive females' preferences. Nonreproductive females have to choose between (a) male and reproductive female; (b) food and reproductive female; (c) food and male.

The results of these experiments can be summarized in the following way. Males always behave in the same manner. They are attracted by reproductive females and they prefer reproductive females to everything else, including food. However, when reproductive females are out of sight they are strongly attracted by food and, since they are always very active and explorative, they eat much food. On the contrary, females behave differently when they are reproductive and when they are nonreproductive. When they are reproductive, females prefer food to males, although they are somewhat slower than males even at reaching food. Furthermore, reproductive females only slightly prefer males to another reproductive female and they have a certain tendency to be attracted by other reproductive (but not nonreproductive) females, thereby increasing the probability to attract males. In all circumstances, their behaviour tends to be slow and hesitant. However, when females become nonreproductive as a result of mating, their behaviour changes radically. They become very active, and in fact almost as active as males. However, contrary to males, they prefer food to everything else and are not attracted by anything else.

4. Different types of food

We have described a number of differences in the behaviour of males and females that evolve in an environment in which there is only one type of food and all food tokens contain the same quantity of energy. We now ask: How do males and females behave with respect to food if they live in a somewhat more complex environment which contains two different types of food? The two types of food have different colours and the neural network controlling the robot's behaviour has separate visual units encoding the two different colours so that the robots can distinguish between the two types of food. Apart from colour, what are the differences between the two types of food?

In the simulation described in the preceding Sections all food tokens contained .50 energy units. The new environment contains the same total number of food tokens, that is, 70 food tokens, but now half of these food tokens contain .75 energy units and half contain .25 energy units. We evolve two populations of robots in two different environments. In both environments one type of food is more energetic than the other type but in the first environment this is the only difference between the two types of food while in the second environment there is a 30% probability that what is normally a more energetic food token will contain no energy but a toxic substance which reduces by 0.1 units the energy of the robot that eats it. In other words, in the second the more energetic food is risky. (As already mentioned, the values of all the simulations' parameters are chosen arbitrarily.) Our question is: Will male and female robots behave differently with respect to the two different types of food in the two environments?

To determine the food preferences of male and female robots, we have tested the best three male and the best three female robots of the last generation of the 10 replications of the new simulations in a controlled environment identical to the controlled laboratory setting used in our basic simulation. The robot is placed in a fixed position in front of two food tokens, one with more energy and the other one with less energy, and we determine which of the two tokens the robot approaches and reaches (or fails to reach) in a fixed period of 5000 time steps. Each trial is repeated twice by changing the right/left position of the two food tokens with the respect to the robot. While male robots are tested only once, female robots are tested twice: when they are reproductive and when they are nonreproductive.

The results are shown in Figure 11 and they can be summarized in the following way. Males do not appear to prefer one type of food over the other and this is true in both environments. In contrast, females have clear food preferences but these preferences are different in the two different environments. If they have evolved in the environment in which the more energetic food is simply more energetic and does not present any risk, females tend to prefer the more energetic food to the less energetic one. However, if they have evolved in an environment in which the more energetic food has some probability to be toxic, they clearly prefer the less energetic but riskless food.

Figure 11. Food preferences of male and female robots for more energetic and less energetic food (a), and for more energetic but risky food and less energetic but riskless food (b).

These results are obtained in a strictly controlled, "laboratory" environment and they can be interpreted as indicating the preferences of male and female robots as they are encoded in their brain (neural network). It is interesting, however, that if we count the number of food tokens of the two types eaten by the robots in their natural environment, we obtain somewhat different results. In the first environment not only females but also males eat more tokens of the more energetic food than of the less energetic food, while in the second environment the situation is reversed and both males and females eat more tokens of the less energetic, but riskless, food than of the more energetic, but potentially toxic, food (Figure 12).

Figure 12. Figure 12. Number of generations in which male and female robots eat more tokens of one or the other of the two types of food (more energetic and less energetic) in the two environments in which the more energetic food is without risk (a) and with risk (b).

This result may be considered as surprising but in fact it indicates an important methodological point. In the controlled conditions of the laboratory we capture the “naked” preferences of the robots for the two types of food in the sense that what the robots do in the laboratory depends entirely on the food preferences which are encoded in their brain. In contrast, in the natural environment a robot’s behaviour is a function not only of its food preferences but also of the environment in which the robot finds itself at any given time. In our simulations the environment has two characteristics: (1) when a food token is eaten, a food token of the same type reappears in a random location in the environment; (2) the environment is social, which implies that it is an environment which depends on, and varies with, the behaviour of the other robots. If a robot has a tendency to eat one particular type of food token, a food token of the same type may reappear in the vicinity of another robot, and this may increase the probability that the other robot will eat a food token of the same type even if the robot has no preference for that type of food. As we have seen, while in the laboratory male robots do not exhibit food preferences, female robots that live in the first environment prefer the more energetic food and those who live in the second environment prefer the less energetic, but more risky, food. Since male robots live in the same environment with female robots, this may explain why our male robots eat more food tokens of the more energetic type in the first environment and fewer food tokens in the second environment, although in the laboratory they do not show any preferences. Another interpretation is that in their natural environment males eat more of the more energetic food because males are always looking for reproductive females and, since reproductive females prefer the more energetic food, males are likely to find the more energetic food near to reproductive females.

To obtain some support for these interpretations we have collected data in two environments which are halfway between the natural environment and the laboratory environment. Consider the robots which evolve in the environment in which half of the food tokens are less energetic but riskless and half are more energetic but potentially toxic. In a first test we have placed a single male robot in an environment which is identical to the natural environment except that the robot is all alone: there are no other males and there are no females. In the second test the environment contains all 50 male robots but there are no females. The results show that in these semi-natural environments, the male robots show no preferences for the two types of food, exactly like in the original laboratory setting. This seems to indicate that male robots do not actually prefer the less energetic but riskless food over the more energetic but risky food, or vice versa, but it is the presence of female robots in their natural environment that causes them to eat the less energetic but riskless food than the more energetic but risky food. It is like human males going to a tea house instead of a pub in order to meet potential females partners, who would not be found in the pub: these males end up sipping herbal tea, even if they would personally prefer drinking beer.

5. Caring for one’s offspring

For the robots we have described so far having offspring is sufficient to leave one’s genes to the next generation. But for many animal species mating and having offspring are not sufficient. Offspring are born without the capacity to feed themselves and, therefore, to survive and reach reproductive age they must be fed by someone else for a more or less long period after birth. And this dependence may take other forms such as protection from predators, cold, and other dangers. Kin selection theory (Hamilton, 1964) predicts that in these species parents (one or both) will feed

their dependent offspring in that only by feeding them they will increase the probability that the copy of their genes will be found in future generations.

Our next robots have a genotype which, in addition to encoding the connection weights of the robot's neural network and the intrinsic activation level of the network units, includes an offspring-care (OC) gene. The OC gene is a number that can vary between 0 and 1, where a value of 0 means that the individual carrying the gene will eat all the food it is able to find while a value of 1 means that the individual will give all of its food to its dependent offspring. Unlike the offspring of our preceding robots, the offspring of these robots are born with an amount of energy which allows them to survive without eating for 600 time steps but at the end of this period they must be fed by someone else for another period of 600 time steps in order to remain alive. The robots of the initial population have a randomly assigned value for their OC gene, with an average value of 0.5, and the gene is inherited with some random changes in its value by an individual's offspring. Hence, like the other parts of the genotype, selective reproduction and random mutations can change the average value of the gene in a succession of generations.

Both male and female robots have the OC gene but we have evolved the new robots in two different conditions. In one condition, the probability that one parent will give its food to its offspring is exclusively determined by the value of its OC gene. In the other condition this is true for mothers but not for fathers. For fathers, assuming that a male robot has decided, given the value of its OC gene, to give its food to its offspring, its offspring will actually receive the food only 50% of the times (while in the other 50% the food simply disappears). In other words, while mothers are certain that the food they give to their offspring actually goes to their offspring, fathers are not so certain. This captures an important fact concerning species in which having multiple mating partners is the norm, which is the case for many mammals, including some human cultures. Whereas females are sure of the identity of their offspring, males may be uncertain if a child is actually their offspring or the offspring of another male.

The results indicate that if the probability that offspring actually receive the food given to them by their parent is 100% (first condition), the evolved value of the OC gene is more or less the same for both mothers and fathers (0.47 and 0.43, respectively) and, as one would have predicted since both mothers and fathers can feed their offspring, it is lower than it was for the populations in which only mothers or only fathers had the OC gene. In contrast, for the population in which fathers, even if they decide to give their food to their offspring, are not sure that the food will actually be given to their offspring, males have a significantly lower value for their OC gene (0.39) compared to mothers (0.52).

We have examined the behaviour of the robots with the OC gene in the same laboratory setting used for the robots lacking the OC gene. Males, reproductive females, and nonreproductive females are offered a choice between two items and we determine which item they choose, how much time they take to choose, and if they simply do not choose. The general result of these experiments is that if robots have offspring which depend on their parent(s) for food, the importance of food for them increases in all the choices they have to make between two different items one of which is food.

6. Discussion

We have described a series of simulations of the evolution of populations of robots which are either male or female and which in order to reproduce have to mate with a robot of the other sex. The only difference between males and females that we have imposed on our robots is that after mating females have a nonreproductive period during which mating does not result in conception, while this is not true for males. Our simulations were aimed at finding out what are the consequences of

this single difference associated with sex for the behaviour of our robots. This is a summary of what we have found.

One basic difference between males and females concerns reproductive success. While both males and females necessarily have the same average number of offspring, the best male has more offspring compared to the average male than the best female compared to the average female. The reason appears to be that males and females are under different selective pressures. Reproductive females are a “scarce resource” for males because at any given time most females (in our simulations, from 30 to 40 out of 50) are nonreproductive. Therefore, males must compete with other males for this scarce resource, and in our simulations finding reproductive females, not eating and living a long life, is the main challenge for them. On the contrary, males are not a “scarce resource” for females because at any given time all 50 males are potential mates. While a male can (theoretically) generate an offspring at each time step, females can generate a maximum of 10 offspring during their entire life. Therefore, for females the challenge is not to find mates but to eat and in this manner to live as long as possible.

The different biological roles that males and females play in reproduction also produce a number of differences in their behaviour. Males tend to always explore actively the environment. They look for reproductive females and they approach reproductive females rather than food. One may ask how males can adopt this strategy if food is necessary for their survival. In fact, contrary to what one would predict on the basis of the preference of males for reproductive females rather than food that we have found in our experiments, males eat more and, on average, live longer than females. The answer is that while males are exploring actively the environment searching for the “scarce resource” represented by reproductive females, they are able to find food and to eat for a sufficient portion of their time. However, as soon as they perceive a reproductive female, males tend to ignore food and to approach and mate with the female.

Reproductive females behave very differently. They do not go after males although, being reproductive, they might successfully mate with them and, even when they go after food, they are not very active and move rather slowly. We can interpret this behaviour of reproductive females by noting that males and females have a different (symmetrical) reproductive strategy: males actively look for reproductive females while reproductive females wait for males to come and mate with them. Not only reproductive females do not search for mates but they do not go actively after food because they prefer to remain where they are so that males may more easily find and mate with them. And in our laboratory experiments we have found a tendency of reproductive females to aggregate with other reproductive females, which appears to be another strategy for attracting males.

Since in our simulations, as in real life, surviving is not sufficient for transmitting one’s genes to the next generation but it is a necessary pre-condition, one may ask how females can survive although they do not look very actively for food. The answer is that the same female which is reproductive will soon become nonreproductive because some male will find and mate with her. And nonreproductive females behave very differently from reproductive females. The same female which, when it is reproductive, is not very active and does not look very much for food, when it has mated and has become nonreproductive, changes its behaviour: it becomes very active and looks actively for food. This strategy allows females to survive. They eat a lot when they are nonreproductive and this compensates for their eating less when they are reproductive - although, overall, they still eat and live somewhat less than males.

Another way to look at the differences in the behaviour of males and females is to say that males have a simpler life in the sense that they are expected to do always the same thing: actively look for

reproductive females and eat food while looking for reproductive females. In contrast, the life of a female includes two different states or periods. When a female is reproductive, she tends not to be very active and to mainly wait for males to mate with her. When she becomes nonreproductive, her behaviour changes. She actively looks for food and ignores everything else.

In summary, although males and females live in the same environment, they have different ecological niches. While the physical environment in which an organism lives is independent of the organism, the ecological niche of the organism depends on the characteristics of the organism, including its feeding and reproductive strategy. This applies to organisms belonging to different species but it also applies to males and females belonging to the same species. Since males and females have different roles in reproduction, their ecological niche is different and this causes a number of differences in their behaviour.

The different adaptive patterns of males and females also emerge in somewhat more complex environments in which there are two different types of food. In these more complex environments males generally do not manifest food preferences: their feeding strategy appears to be to eat whatever food they happen to encounter while they are actively exploring the environment searching for reproductive females. In contrast, females are more discriminative. Since their main adaptive challenge is to live as long as possible, they have a preference for the more energetic food over the less energetic one, although when the more energetic food has some probability to be toxic, they exhibit an opposite preference for the less energetic food over the more energetic one.

Other differences in the adaptive pattern of males and females manifest themselves when to leave one's genes to future generations it is necessary not only to have offspring but also to feed one's dependent offspring. While both fathers and mothers have the same tendency to give their food to their dependent offspring when parental certainty is as great for males as for females, when males are less certain than females that they are really feeding their offspring, males are less disposed to feed their (supposed) offspring than mothers are disposed to feed their (sure) offspring.

As we have noted in the Section 1, our robots are not aimed at reproducing any specific species of animals. They are very simplified, "general", (simulated) animals. However, the differences in behaviour between our male and female robots also tend to be found in many real animals: a greater variance in reproductive success, a greater tendency to actively explore the environment and, consequently, to learn more about the environment (Gaulin and Fitzgerald, 1989; Brandner, 2007), and a greater tendency to exhibit risky behaviour in males than in females (Harris, Jenkins and Glaser, 2006; cf. the simulation in which the more energetic food can be toxic), a greater importance of mating compared to eating in males compared to females (Trivers, 1972), a greater investment in one's offspring (by feeding them) in females than in males if males have less parental certainty than females (Geary, 2000).

The greater investment in one's offspring of females compared to males is attributed to a variety of factors. One of these factors is the different size of the female egg cell compared to the male sperm cell: the egg cell is much larger and it needs much more energy to survive than the sperm cell. However, one has to consider that the number of egg cells produced by a female is much smaller than the number of sperm cells produced by a male. (For a criticism of the interpretation of the different reproductive investment of males and females in terms of male and female cell size, see Dewsbury, 1982.) Another factor is parenting effort, which is greater in females than in males in that females spend more of their energy in assisting their offspring after conception, both in uterus and after birth, compared to males. Our simulations show that even in the absence of these factors females invest more than males in their offspring due to the smaller number of offspring that they

can possibly have and to their greater parental certainty compared to males. (For a discussion of paternal investment in mammals, cf. Clutton-Brock, 1989; 1991.)

Before we close this discussion we want to stress once more that our robots are extremely simplified with respect to real animals and they are not intended to reproduce any particular species of animals. To give an example, we find that the average male robot lives longer than the average female robot while in many real animals (Bronikowsky, 2011; Clutton-Brock and Isvaran, 2007) the opposite is true: females live longer than males. What should be done is add other factors which are currently ignored in our simulations and see whether the behaviour of our robots, including their mortality, matches the behaviour and mortality pattern of real animals. For example, movement has no costs for our robots. If, more realistically, we add movement cost, males might have a shorter life than females because they move more than females. Or, males may physically compete with other males for access to females and this may also result in a shorter life length of males compared to females.

7. Directions of future research

In this last Section we describe some further directions of research that might be explored by using our male and female robots.

(a) Families

One interesting direction of research is to study the emergence of families as groups of genetically related robots that tend to live near to each other and to interact with one another. This will require a number of changes in our robots. First, while in the present simulations nonreproductive females move as easily as reproductive females, during their nonreproductive period females should not be able to move as easily as when they are reproductive and this may imply a need for them to be fed by their mates or to search for food locally and for specific types of food (foraging rather than hunting). Second, while in the present simulations offspring are virtual and they are fed virtually, the offspring should be real robots which live in the same environment with their parents (generational overlap) and both mothers and fathers should not be able to feed their dependent offspring unless they are spatially close to their offspring and therefore to each other. Third, to increase the probability of feeding their offspring and not the offspring of other males (paternal certainty), fathers should remain in proximity to their wives. (For a discussion of the social factors shaping men's role in modern families, see Lewis and Salt, 1986.) An important implication of the emergence of families is that the life of robots should be linked to specific places (nests, homes), with the robots possessing the ability to recognize and to remember the spatial location of these places (Ecuyer-Dab and Robert, 2004b).

(b) Sexual attractiveness

The robots described in this paper are categorically (male, reproductive females, nonreproductive females) but not individually different. If each individual robot is different from all the other robots and the robots can perceive these differences, this may help husband and wife robots to recognize each other, which may be important for the emergence of families. But what is more interesting is that we might be able to study sexual attractiveness (beauty) in our robots and sexual selection by the members of the other sex. If the robots have physical characteristics which are correlated with the probability of leaving their genes to the next generation, a robot that possesses these characteristics may be preferred as sexual partner by a robot of the opposite sex to other robots which lack them. These characteristics may be different for male and female robots. Male robots may be chosen as mates by females if they have physical characteristics which are correlated with

their ability to find food or to defend their wife and offspring from dangers. Female robots may be chosen as mates by males if they have characteristics correlated with their ability to give birth more easily to offspring, to give birth to healthier offspring, to feed their dependent offspring with their milk, and to interact in a caring way with their offspring (Dixson, Grimshaw, Linklater, and Dixson, 2010).

Male attractiveness may also be related to other characteristics possessed by males. The male robots described in this paper compete in a Darwinian sense with each other for the scarce resource represented by reproductive females. But male robots may also compete with each other behaviourally, by fighting, by showing off, and in other ways. The physical characteristics of males which are correlated with their ability to win these behavioural competitions with other males may be another component of male “beauty”, and females may prefer a more “beautiful” male as mating partner. But the greater importance of sexual selection for males than for females (for a classical example, cf. Bateman, 1948; for a recent assessment, cf. Dewsbury, 2005; also see Fernandez-Duque, Vallengia, and Mendoza, 2009) can already be captured with our simulations since females are a “scarce resource” for males. Another thing to consider is that human females may like different physical characteristic of males when they are reproductive and when they are nonreproductive (Penton-Voak and Perrett, 2000) and this may be associated with the existence of recreational sex (mating between males and nonreproductive females) and with “invisible fertility” in females (Diamond, 1998), which are both absent in the simulations described in this paper.

(c) Emotional states and their expression

All animals have many different motivations (for example, eating and flying away from a predator or eating and mating) and, since they generally cannot pursue more than one motivation at the same time, it is critical for them to decide appropriately which motivation to pursue at any given time in order to maximize their survival/reproductive chances. Emotional states have emerged to allow animals to make better motivational decisions, i.e., decisions which are more correct, faster, and generally more effective. In previous research (Ruini, Petrosino, Saglimbeni, and Parisi, 2010; Parisi and Petrosino, 2010) it has been shown that adding a special “emotional circuit” to the neural network of robots that have many different motivations tends to make their behaviour more effective and to increase their survival/reproductive chances. Mating and caring for one’s offspring are very important motivations and, therefore, an interesting direction of research is to add an “emotional circuit” to the neural network of our male and female robots and to study if there are differences between the emotional states of male and female robots.

Emotional states are based on the interaction of the brain with the rest of the body and they may imply changes not only in the internal organs and systems of the body but also in the posture, movements, and other external characteristics of the body which may be perceived by other robots. This “expression of emotions” will allow one robot to let other robots know its emotional states, and this knowledge may influence the motivational decisions of other robots. Again, mating and caring for one’s offspring are an area in which the expression of emotions plays an important role, inviting or rejecting mating attempts, establishing attachment between parent and offspring, etc. The expression of emotions which are related to sex and parenting may be another topic of research that can be studied with our robots.

(d) Female menopause and grandmothers

Unlike other primates, after a certain age human females become permanently nonreproductive (menopause). Female robots that have menopause may allow us to ask why females continue to live after menopause and to explore the “grandmother hypothesis” according to which post-menopause

females continue to live so that they can help their daughters to take care of their offspring (Hawkes et al. 1998; Hawkes, 2004).

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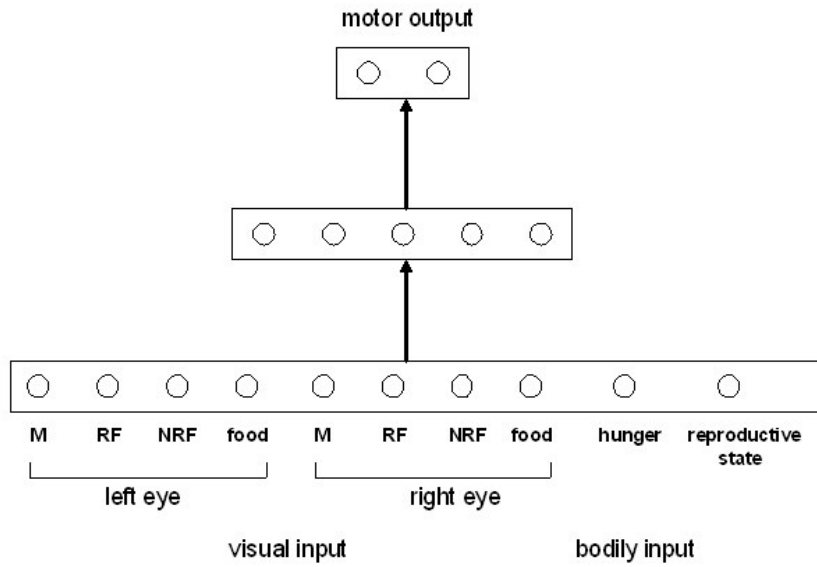


Figure 1. The neural network that controls the behaviour of the robots. Visual input originates in the external environment. Hunger and female reproductive state are inputs originating within the robot's body. The bodily input that signals the current reproductive/nonreproductive state of the robot exists only for female robots.

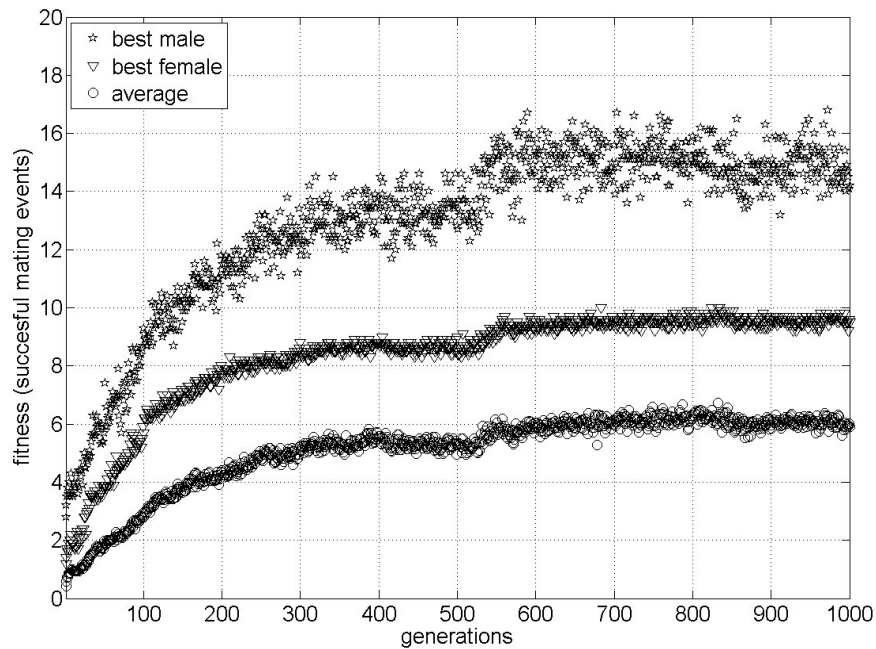


Figure 2. Average number of successful mating events and number of successful mating event for the best male and the best female across 1000 generations (average of 10 replications of the simulation).

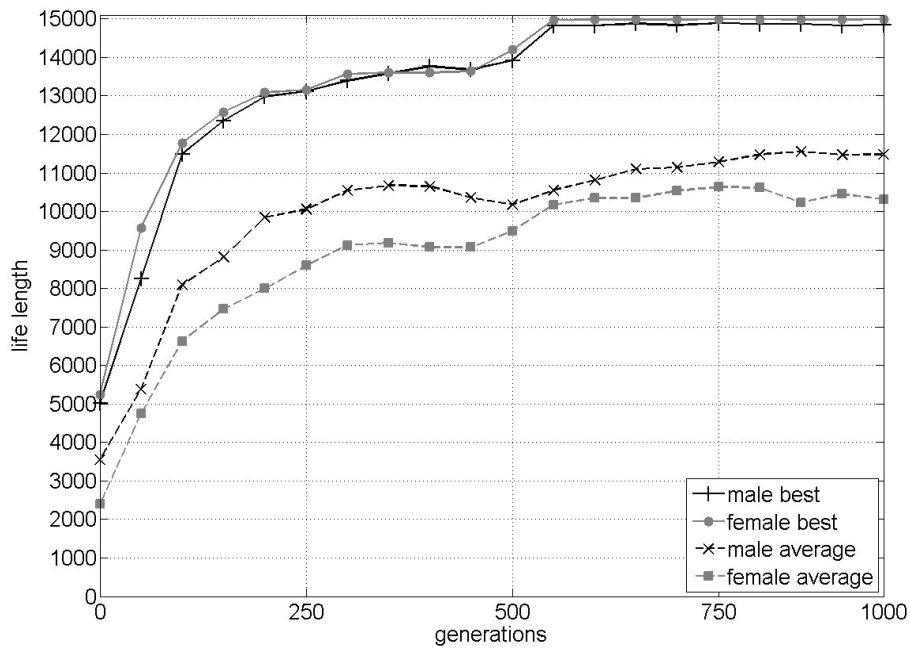


Figure 3. Life length for best male and female robots and for average male and female robots.

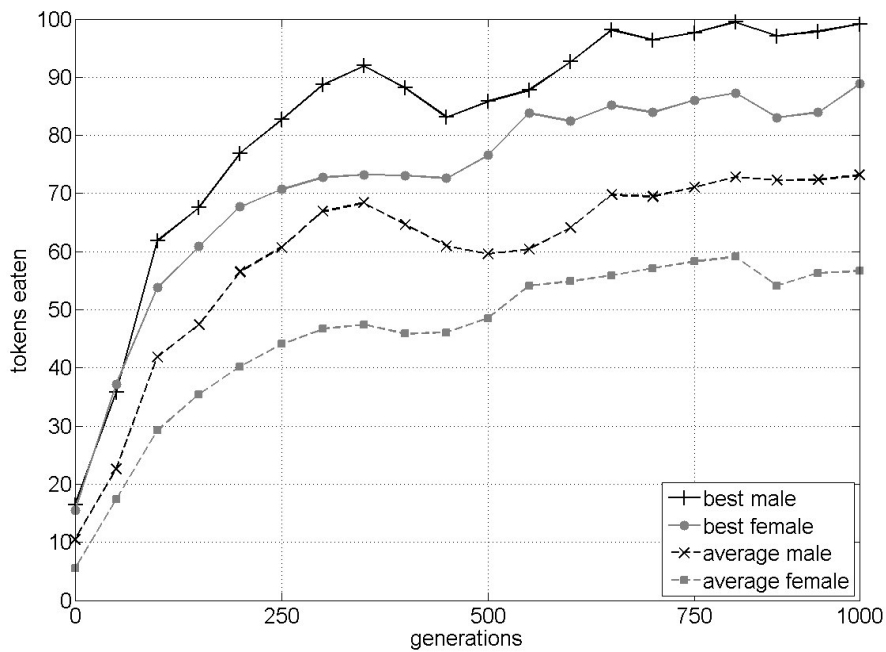


Figure 4. Number of food tokens eaten by best and average males and best and average females across 1000 generations.

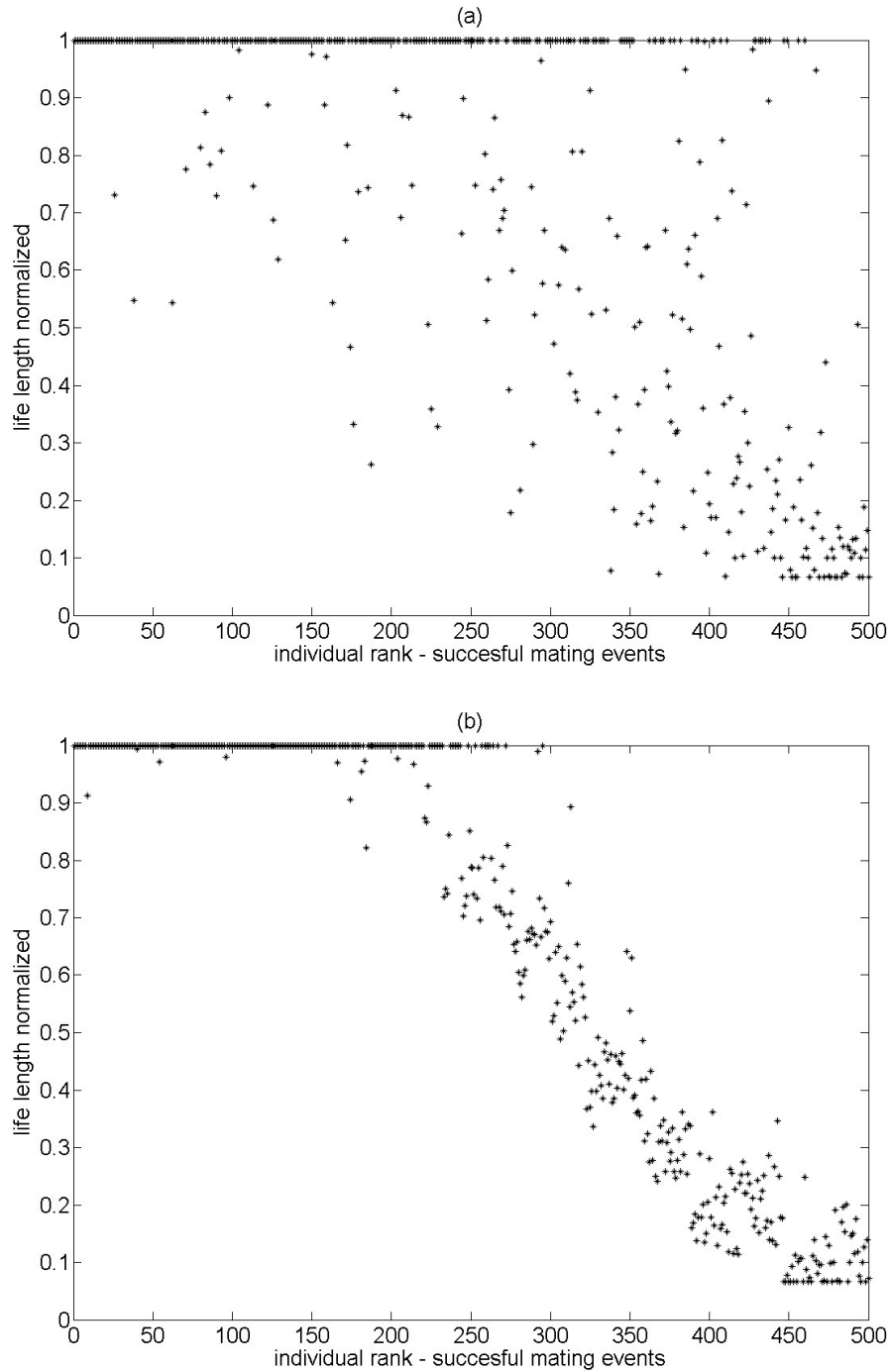


Figure 5. How ranking in reproductive success and length of life are related in males (a) and females (b).

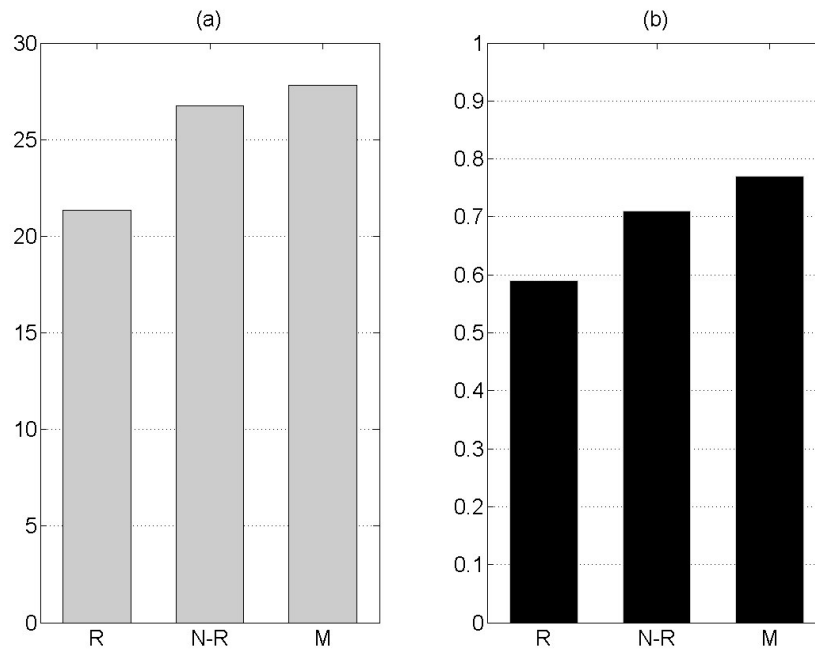


Figure 6. (a) Number of different environmental zones visited by males, reproductive females, and nonreproductive females. (b) Difference between the activation levels of the two motor units (speed of the two wheels) for males, reproductive females, and nonreproductive females. The difference is computed according to the formula $\theta = (m_1 + m_2) \sqrt{m_1 m_2}$.

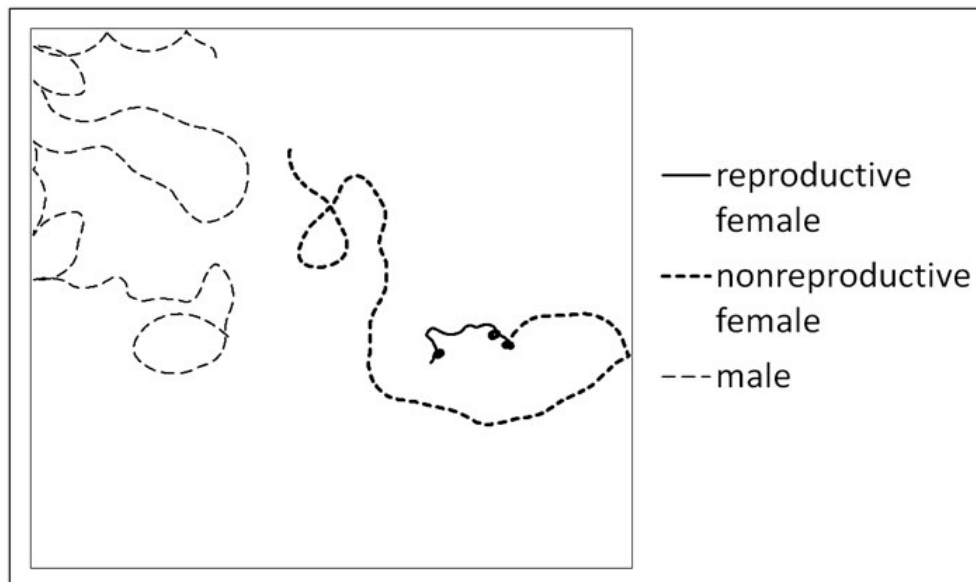


Figure 7. Path followed by a male during 1900 time steps, by a nonreproductive female during 950 time steps, and by the same female when she becomes reproductive during a further period of 950 time steps.

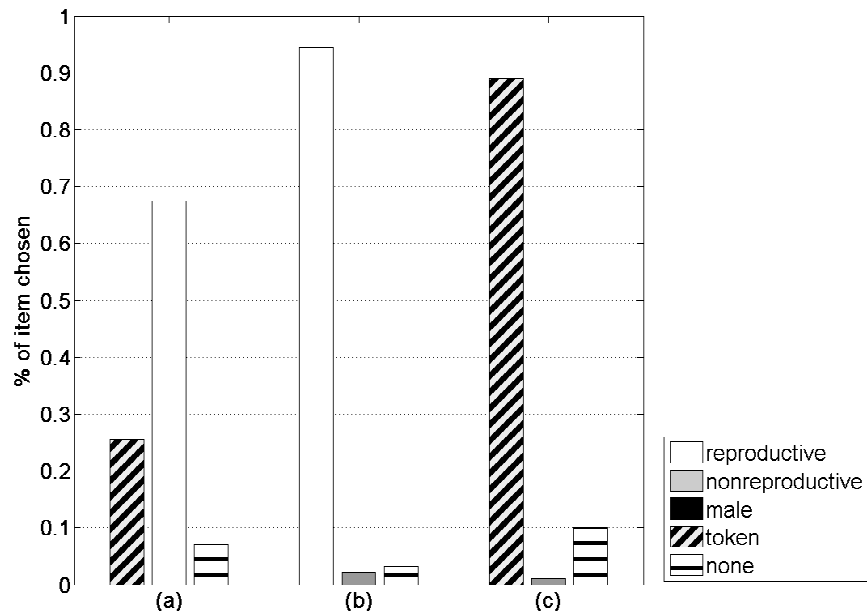


Figure 8. Males' preferences in the laboratory experiment. Males have to choose between (a) food and reproductive female; (b) reproductive and nonreproductive female (c) food and nonreproductive female.

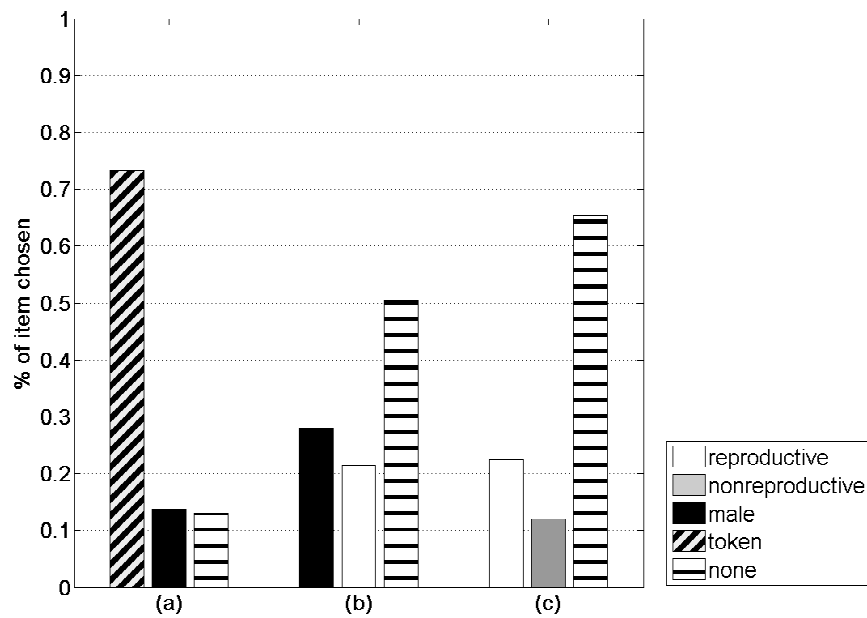


Figure 9. Reproductive females' preferences. Reproductive females have to choose between (a) food and males; (b) male and reproductive female; (c) reproductive and nonreproductive female.

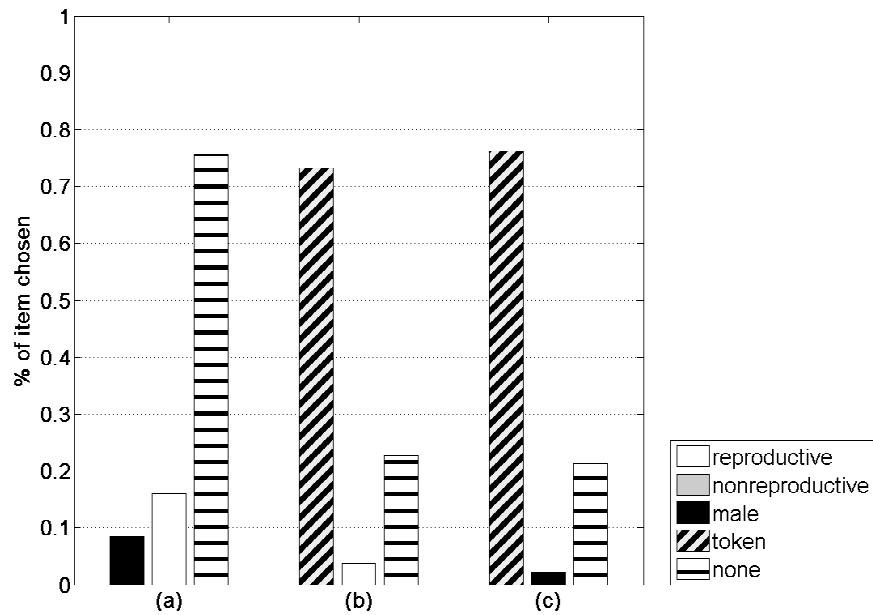


Figure 10. Nonreproductive females' preferences. Nonreproductive females have to choose between (a) male and reproductive female; (b) food and reproductive female; (c) food and male.

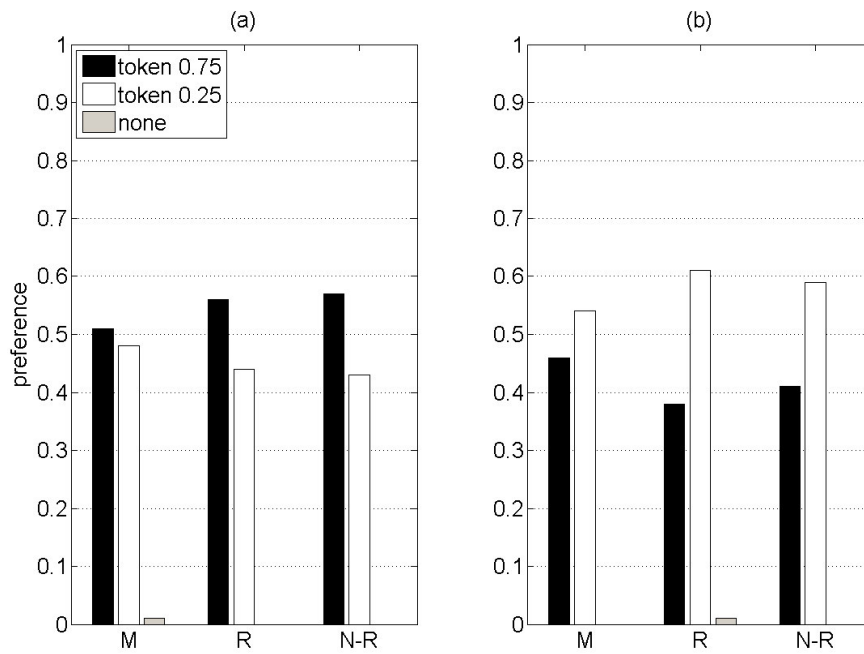


Figure 11. Food preferences of male and female robots for more energetic and less energetic food (a), and for more energetic but risky food and less energetic but riskless food (b).

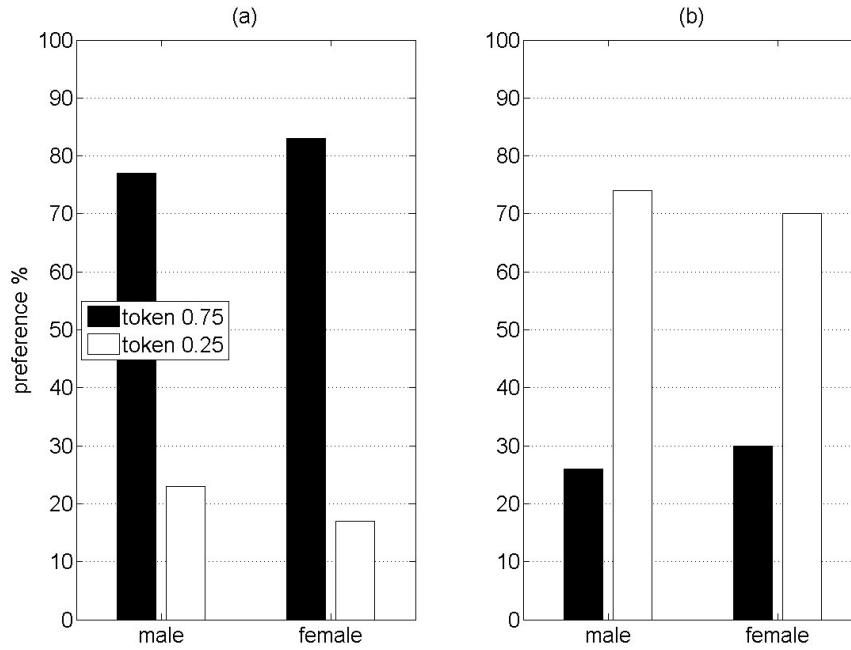


Figure 12. Number of generations in which male and female robots eat more tokens of one or the other of the two types of food (more energetic and less energetic) in the two environments in which the more energetic food is without risk (a) and with risk (b).