Symmetrical strategy

In this document we describe the best evolved individual of the best replication of the experiment performed on a 110x110 cm environment which displays a symmetrical strategy.

Motor and communication behaviours repertoire

The analysis of the evolved robots indicates that they exhibit the following signalling and motor behaviours:

- A **signal-A** behaviour which consists in the emission of a signal in the range [0.7 to 0.9] which is produced robots located outside target areas detecting a signal greater than 0.3. The fact that the production of this signal is influenced by the perceived signal implies that this signal is only produced when both robots are located outside target areas.
- A **signal-B** behaviour which consists in the emission of a signal in the range [0.4 to 0.6] which is produced by robots located in target area #1.
- A **signal-C** behaviour which consists in the emission of a signal in the range [0.0 to 0.3] which is produced by robots located in target area #2 or by robot located near obstacles. The value of the signal produced by robots located in target area #2 increases from 0.0 to approximately 0.3 as the time spent by the robot in the area increases.
- An **obstacle-avoidance** behaviour which consists of a sequence of right-turning actions performed near an obstacle constituted by a wall or by another robot through which the robot turns on the spot until the frontal side of the robot is free from obstacles. This behaviour is produced when the frontal-right infrared sensors of the robot are activated.
- A **move-straight** behaviour which consists of a sequence of move forward actions. This behaviour is produced by robots located outside target areas or robots in target area #1 which detect signal A.
- A family of **right-turn** behaviours, which consists of a sequence of right-turning actions through which the robot moves forward and turns right by producing an arc trajectory over a circle with a diameter ranging from a few mm up to 100 cm. This family of behaviours is produced by robots detecting signal B or C or by robots located in target area #2 detecting signal A. The turning displayed in different instances of this behaviour depends on three factors (and on their combination): the value of the signal, the location of the robot and the time spent by the robot in the current location (for robots located in target areas). More precisely, the turning angle displayed by the robot is inversely proportional to the value of the detected signal, and increases or decreases over time for robots located in target area #1 and #2, respectively. For example, the diameter of the arc trajectory produced by robots located outside target areas varies within the range [5, 100] cm for signals in the range [0.0, 0.3]. For robots located in target areas and detecting a signal of 0.5, the diameter of the arc trajectory decreases from 100 to 0 or increases from 5 to more than 100 cm over time, for target area #1 and #2 respectively.
- A **move-toward-robot** behaviour which consists of a sequence of move-forward and right-turning actions which allows a robot which visually perceives another robot to move toward the latter robot and to keep it in the view field for a certain period of time. This behaviour is produced by robots perceiving signal B or C and having the other robot in their field of view. Since the ability of the robots to maintain the other robot in their field of view is limited and since this behaviour is produced only when this condition holds, the execution of this behaviour might terminate after some time. The probability that this behaviour is terminated depends from the relative movement of the visually perceived robot. In fact, robots never loose visual contact of other robots which stay still

or move within a target area while they tend to quickly loose visual contact of other robots displaying an exploration behaviour.

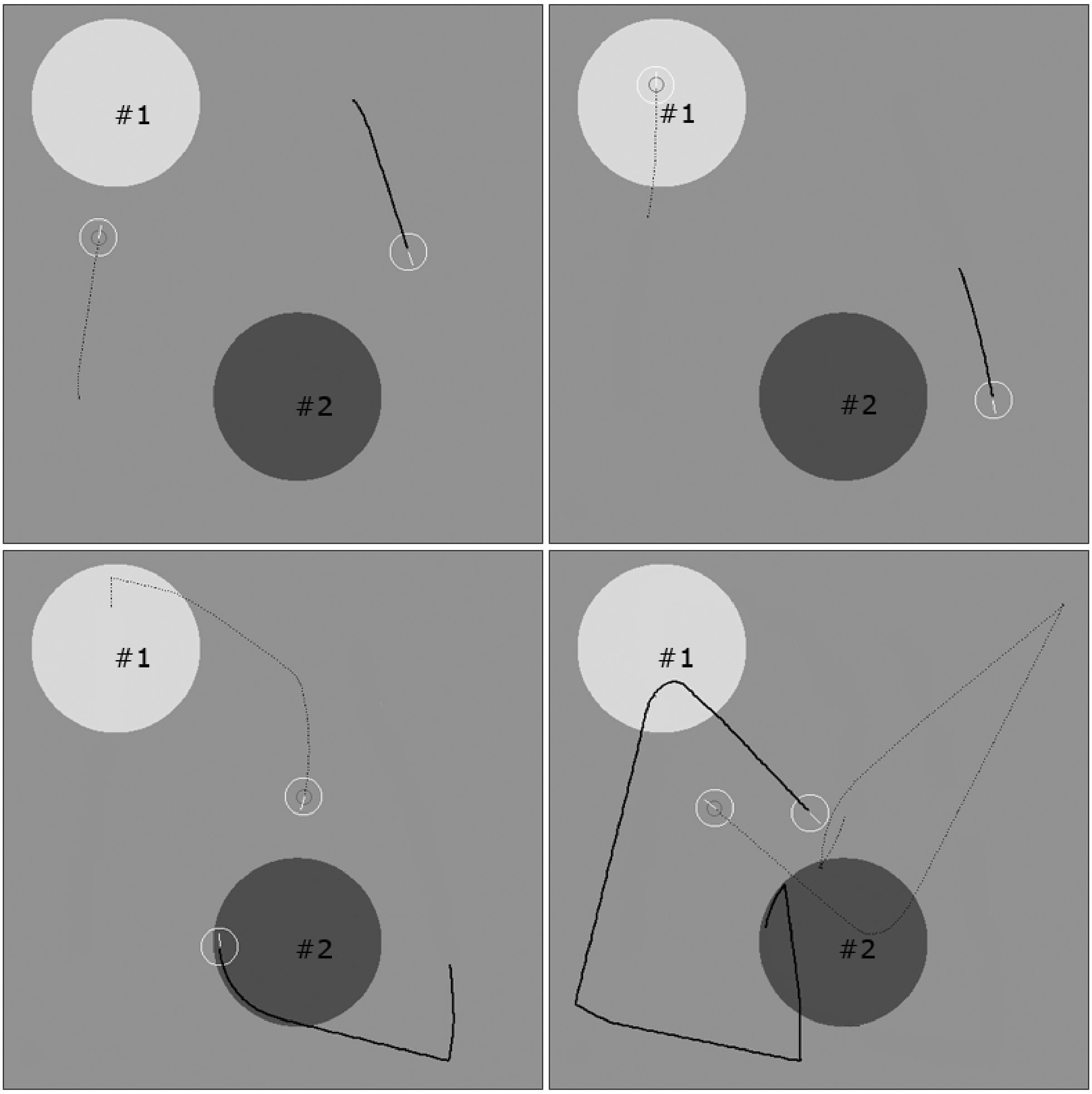


Figure 1. The behaviour produced by the best robots of the best replication of the experiment performed in the 110x110 cm arena. The 4 pictures show 4 snapshots of the trajectory produced by the robots from 0 to 4, 4 to 9, 9 to 21 and 21 to 53 seconds (from left to right and from top to bottom, respectively). The black and grey lines represent the trajectory of the two robots during the corresponding phases.

To illustrate how the combination of these behaviours allows the robots to solve their collective task, let us consider a typical trial in which the two robots are initially located outside target areas (Figure 1, top-left). In this situation the robots display a move-straight and signal-A behaviour when they are far from obstacles and an obstacle-avoidance and signal-C behaviour near obstacles. The combination of the move-straight and obstacle-avoidance behaviour allows the robots to explore the environment. The role of the signal-A produced by each robot is to trigger the move-straight behaviour in the other robot. The obstacle-avoidance behaviour, instead, is triggered by the activation of the frontal-right infrared sensors independently from the detected signal (i.e. the obstacle-avoidance behaviour subsumes the move-straight behaviour). The signal C produced during the execution of obstacle-avoidance behaviour does not have an adaptive function. Indeed, a comparison of the fitness measured in a normal condition and in a condition in which the robots are forced to produce signal-A rather then signal-C nearby obstacles did not produce significantly different performance (results not shown).

When a robot enters in target area #1 it keeps producing the move-straight behaviour and modifies its signalling behaviour from A to B while the other robot keeps producing the move-straight and signal-A behaviour (Figure 1, top-right). The production of the signal-B behaviour during this phase therefore does not have any adaptive function.

When the first robot enters in target area #2 and the second robot is still outside target areas (Figure 1, bottom-left), the former robot produces a right-turn and signal-C behaviour followed by, when this robot exits the area, a move-straight and signal-A behaviour. The latter robot, instead, produces a right-turn behaviour followed by a move-straight behaviour or a right-turn, move-toward-robot and move-straight behaviour. The move-toward-robot behaviour, which is triggered when the latter robot visually detect the former robot, allows the latter robot to turn toward the direction of the former robot (i.e. toward the direction of target area #2). When this happens, i.e. when the latter robot visually perceives the former robot, the combination of the behaviours described above produces a coordinated behaviour in which the two robots turn right, move toward each other by keeping the other robot on the right side of their field of view and then separate again by moving in opposite directions. Let us refer to this sequence of coordinated behaviours as position-exchange behaviour since it leads to a state in which each robot roughly assumes the relative position and orientation previously assumed by the other robot.

The fact that the execution of a position-exchange behaviour produces the re-establishment of the conditions that triggered it in the first place implies that this behaviour tends to repeat itself periodically. The fact that the position and the orientation of the two robots before and after the execution of this behaviour is similar but not identical, ensures that the two robots keep moving in and out target area #2 (thus preserving information on that location) while exploring different parts of the environment at the same time. This allows the robots to also identify the location of target area #1.

The execution of a position-exchange behaviour from a situation in which the two robots are concurrently located in the two target areas, instead, leads to the re-establishment of the same initial positions and orientations of the two robots which, in turn, lead to the production of a periodic target-switching behaviour in which each robot moves toward the target area previously occupied by the other robot.

The difference in the outcomes of a position-exchange behaviour observed when this behaviour is initiated from a situation in which the two robots are located in the two target areas and in a situation in which only one robot is located in target area #2 are due to the fact that in the former case the other robot produces a signal B while in the latter case it produces a signal A. In fact, robots located in target area #2 and perceiving signal B increase their angle of turn over time and trigger a move-toward-robot behaviour as soon as they visually detect the other robot. On the contrary, robots located in target area #2 perceiving signal A do not increase their turning angle over time and do not trigger the move-toward-robot behaviour.

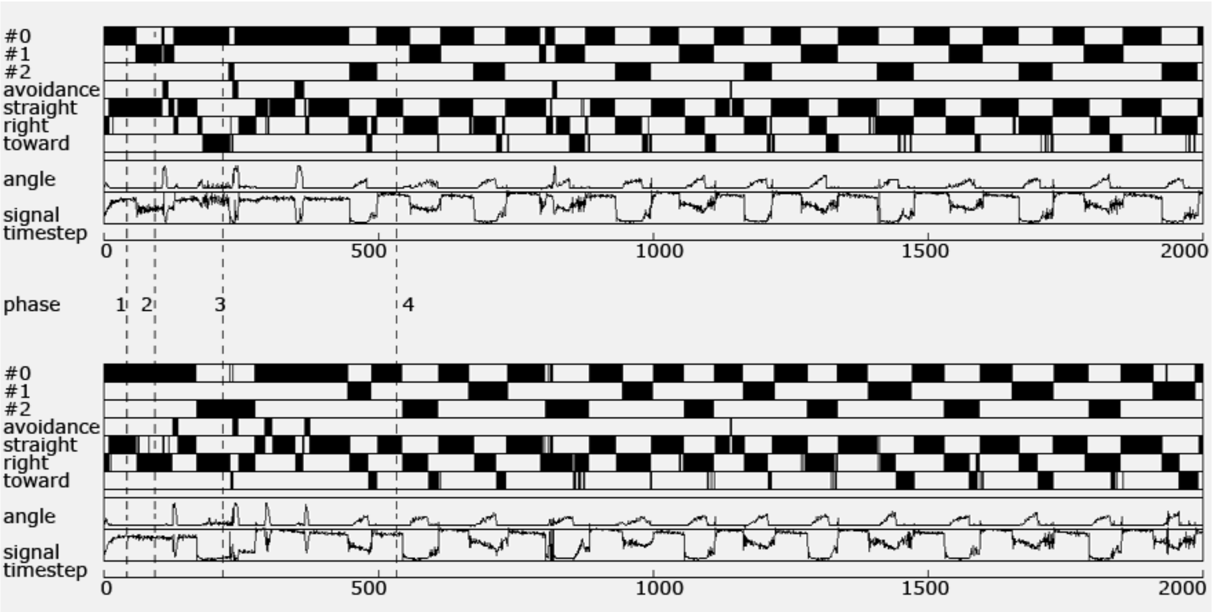


Figure 2: Analysis of the behaviour displayed in Figure 1 throughout time, the 4 phases indicated by the dashed lines correspond to the 4 pictures in Figure 1. The top and the bottom graph show the data relative to the first and the second robot indicated with grey and black lines in Figure 1, respectively. For each graph, the top part indicates the location of each robot (#0 = outside target areas, #1 = in target area #1, #2 = in target area #2). The middle part indicates the elementary behaviour exhibited by the robot (avoidance = obstacle-avoidance, straight = move-straight, right = right turn, toward = move-toward-robot). The bottom part shows the amplitude of the angle of turn which characterizes different instances of behaviours belonging to the turn-right behaviour family and the value of the emitted signal.

Communication system

The arbitration between different behaviours and the coordination between the robots is regulated by the social interaction between the two robots, mediated by the evolved communication system. This system includes the behaviours which enable the robots to access information which has a communicative value, the implicit and explicit signals produced by the robots and the effects produced by the perception of these signals.

The behavioural skill which allows the robots to access useful information, in the case of this replication of the experiment, consists of an exploratory behaviour which allows the robots to find the two target areas. Since the robots keep moving in all environmental situations, the information concerning the location of a particular target area is accessed and communicated by the robot travelling over the area only for a limited period of time. However, when the two robots enter in a coordinated phase, the information on the location of previously visited areas is preserved in the relative position and orientation of the robots. This means that evolved robots are also able to preserve and to implicitly communicate information about previously experienced sensory states.

The signals produced by the robots include three explicit signals (A, B, and C) and an implicit signal constituted by the presence or absence of a second robot in the view field of first robot. More precisely, the signals B and C encode whether the robot is located in target area #1 or #2. The implicit signal encodes the relative location of the robot emitting the signal. The combination of the implicit and the explicit signals B and C encode roughly the relative directions of target area #1 and #2. The signal A instead encodes whether both robots are located outside target areas. This information does not only concern the state of the robot emitting the signal but the state of both robots. Indeed, the information conveyed by this signal is generated through the communicative interaction of the two robots.

The effects of signals consist in the modification of the robots' motor behaviour which is context dependent (i.e. the type of effects produced by a signal and/or whether or not a signal produces an effect depends on the state of the robot detecting this signal). More precisely:

The combination of **signal-A & no-implicit-signal** (i.e. the signal-A combined with the absence of an implicit signal) triggers a move-straight behaviour in robots located outside target areas and far from obstacles.

The combination of **signal-B & no-implicit-signal** triggers: (1) a move-straight behaviour in robots located outside target areas and far from obstacles and (2), a right-turn behaviour in robots located in target area #1.

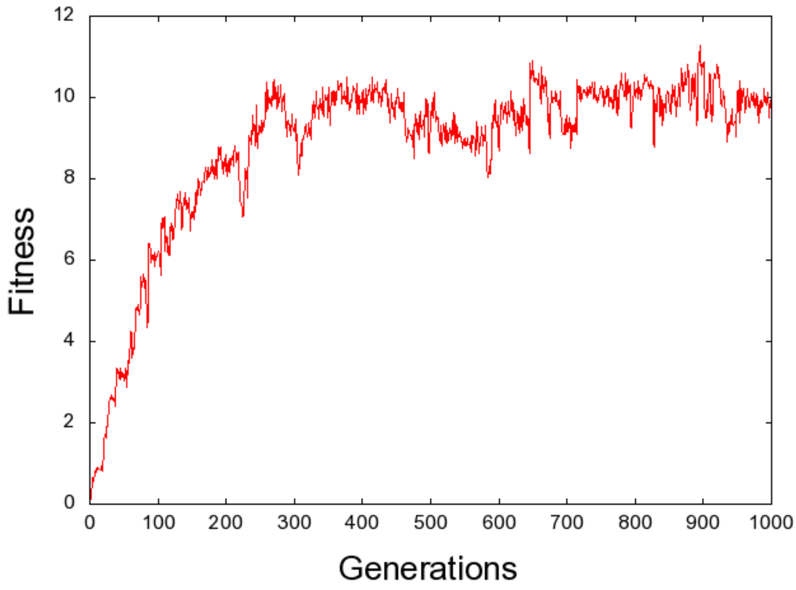
The combination of **signal-C & no-implicit-signal** triggers a right-turn behaviour. The turning angle which characterizes the right-turn behaviour varies depending on the location of the robot detecting the signal and on the time spent by the robot in that location (in case of target area #1 and #2).

The **implicit-signal,** i.e. the perception of the other robot in the view field independently from the type of perceived explicit signals, triggers a move-toward-robot behaviour.

In most of the cases, the explicit signal produced by a robot encodes information which is currently available to the robot through its sensors. However, in some cases, signals also encode information concerning the sensory states previously experienced by the robot emitting the signal. This is the case of the value of the signal-C which encodes not only the fact that the robot is located in target area #2 but also the time spent by the robot in that area (the value of the signal increases from 0.0 to 0.3 as a function of time spent by the robot in that area). The time duration information conveyed by signal-C is exploited to increase the robots' performance. Indeed, by testing the robots in a control condition in which robots located in target area #2 are forced to produce a signal 0.0 independently from the time spent in the area, we observed a drop in performance from 9.673 to 4.189. The analysis of the behaviour displayed by the robots in the control condition indicates that the loss of performance can be mainly ascribed to the fact that the impossibility to increase the value of the signal from 0.0 to 0.2/0.3 produces a modification on the other robot's behaviour which turns too much toward the robot located in target area #2. This in turn causes the robot exiting from target area #1 to move directly toward the robot exiting from target area #2 so that the two robots are then forced to avoid each other and consequently loose the information about the relative location of the target areas. On this aspect see also the data provided in the following section.

Evolutionary origin of robots' communicative and non-communicative skills

In the case of this replication, the performance increases during the first 250 generations until a relatively stable state is reached both in terms of performance and in terms of the robots' behaviours (Figure 3, left). From the very first generation up to generation 20 the robots display an obstacle-avoidance behaviour close to obstacles, a move-straight/right-turn behaviour outside target area #1 and a left-turning behaviour in target area #1. In this initial stage, the robots also produce a signal-C or a signal-B depending on whether they are located inside or outside target area #2. These behaviours allow the robots to explore the environment by occasionally reaching the two target areas at the same time. The robots also modulate their behaviour as a consequence of the implicit signal constituted by the visual perception of the other robot (which tends to trigger a move-toward-robot behaviour) and of the detection of the signal-C (which tends to trigger a turn-right behaviour characterized by an angle of turn which is inversely proportional to the value of the detected signal). However, these interactions mediated by implicit and explicit signals do not lead to forms of coordinated behaviour with an adaptive function.



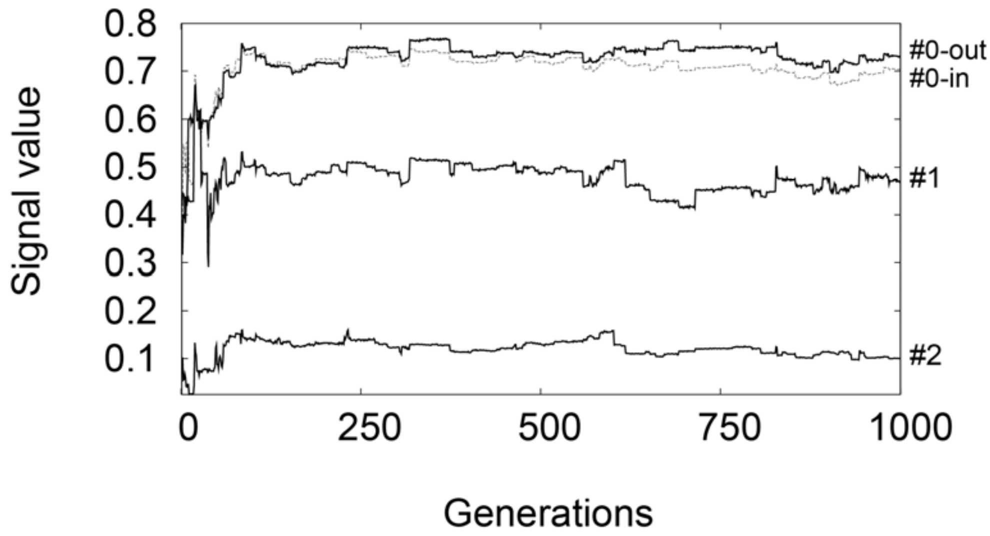
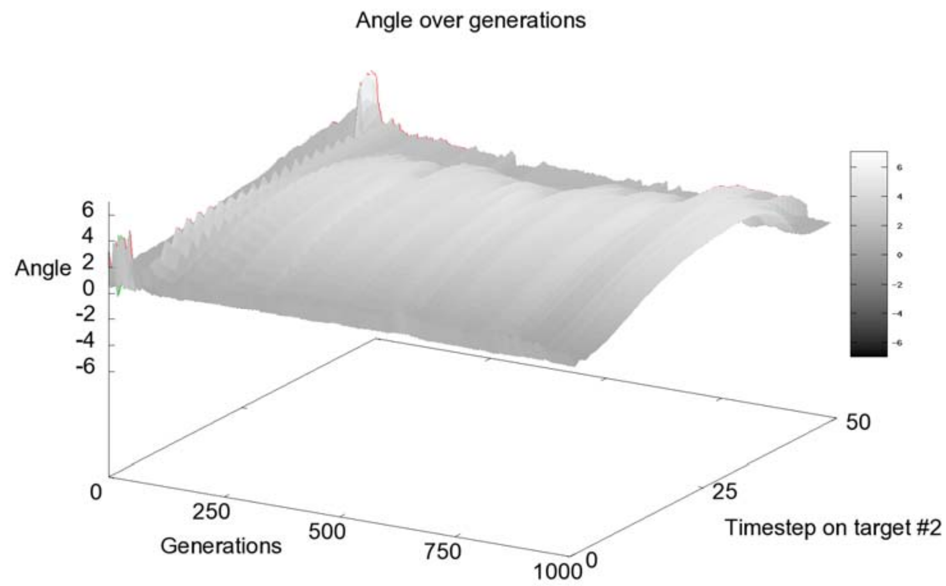


Figure 3. Top: fitness through out generations. Data calculated by testing the ancestors of the best individuals of the last generation for 1000 trials. Bottom: Average value of the explicit signals produced by robots located in target area #1 (#1), in target area #2 (#2), and outside target areas (#0-in, #0-out). For the last case the two curves indicate the average signal produced by a robot when the other robot is located inside a target area (#0-in) or outside target areas (#0-out).

From generation 20 to generation 30, the left-turning behaviour originally displayed in target area #1 is replaced with a move-straight behaviour and the move-straight behaviour originally displayed in target area #2 is replaced with a right-turning behaviour. At the end of this phase the robots further differentiate their explicit signals by producing signal-B when they are located in target area #1 and signal-A when they are located outside target areas. The number of signals produced by the robots and the value characterizing the different signals will remain rather stable from this phase on. As in the previous phase, the robots react to signal-C by triggering a behaviour of the right-turn family and to the implicit signal constituted by the visual perception of the other robot by triggering a move-toward-robot behaviour. This allows the robots to occasionally switch their areas at least once without resorting in exploration behaviour. The right-turning behaviour produced by robots concurrently located in the two target areas (which is triggered by being in area #2 for the first robot and by detecting the signal-C produced by the first robot located in area #2 for the second robot), in fact, increases the chance that the two robots will visually perceive each other and will trigger a move-toward-robot behaviour.

From generation 31 to generation 40, the robots improve their ability to exploit the available signals by modifying the way in which they react to detected signals. Indeed, from now on, the robots react to the detection of signal-A by producing a move-straight behaviour and to the detection of signal-B and signal-C by producing different types of right-turning behaviours. Moreover, robots located in target area #2 differentiate their behaviour depending on whether the other robot is concurrently located in target area #1 or not. Indeed, during this phase, robots located on target area #2 develop an ability to turn-right sharply or to move straight depending on whether they detect a signal B or A, respectively (i.e. depending on whether the other robot is currently located on target area #1 or not). This in turn allows the robots to develop an ability to occasionally switch areas by navigating directly toward the area previously occupied by the other robot.

From generation 41 on, the general strategy and the characteristics of the implicit and explicit signals remain substantially the same. However, the exact way in which the implicit and explicit signals regulate the behaviour of the robots in different conditions is progressively modified through out generations so to maximize performance. These modifications affect in particular the way in which the turning angle which characterizes the right-turning behaviour varies as a function of the time spent by the robot in the target areas, the characteristics of the move-toward-robot behaviour, and the modulation of the value of the signal-C behaviour. As an exemplificative case we show in Figure 4 how the angle of turn and the value of the signal produced by robots located in target area #2 varies as the time spent in the area increases for individuals of successive generations. The analysis of the correlation between the variations of these values and the variations of the fitness throughout generations indicates that some of the variations are adaptive. This is the case, for example, of the variation in the turning angle which occurs at generation 66 and is later preserved in successive generations (Figure 4, top).



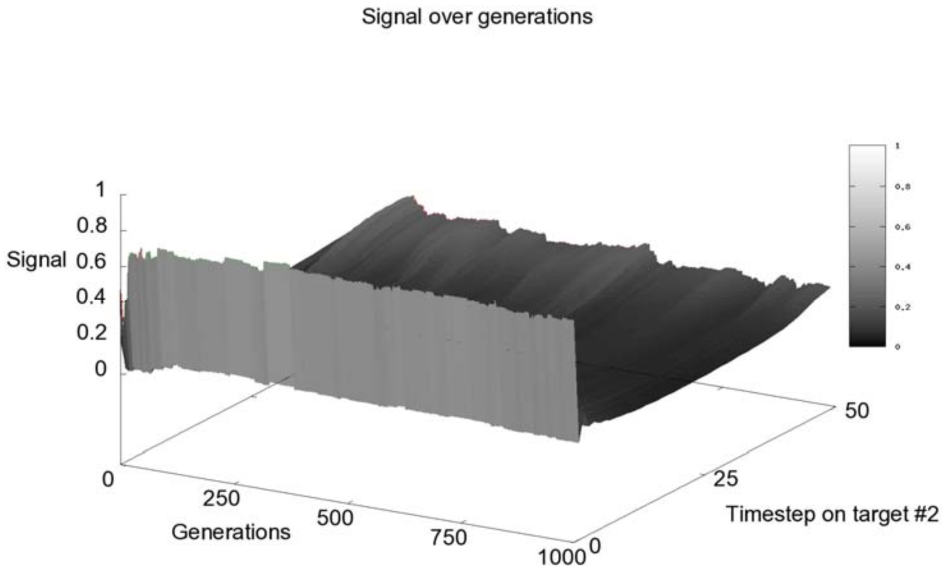


Figure 4. Average turning angle (top) and signal (bottom) displayed by robots in target area #2. Each picture shows how the corresponding value varies as the time spent by the robot in the area increases for individuals of different generations. Data is computed by testing the ancestors of the best evolved individual of the last generation for 1000 trials.