# Behavioural Coordination in Acoustically Coupled Agents

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## Abstract

Approaching behaviour is studied in simulated agents interacting acoustically. A genetic algorithm is used to evolve a fully recurrent, continuous neural network for controlling the agents. Evolved agents actively discriminate the location of external sources of sound. Their own signalling behaviour is integrated with their search behaviour and sensor gain regulation through *self-hearing.* Coupled agents show signs of structural congruence as they perform dancing patterns in space, while the same agents behave very differently when acting on their own or in the presence of a source of sound that imitates their signal patterns.

## 1 Introduction

From the days when W. Grey Walter [2] wired a light bulb into the steering-motor circuit of his phototactic *M. Speculatrix* and let two of them dance around the lab floor until relatively recently, attempts to study the behavioural basis of social coordination have been few and far between. Much of the work in biology concerning social behaviour has concentrated in understanding the functional aspects of coordination between organisms and their stability under evolutionary pressures, despite many well-known cases where the strictly *behavioural* aspects are the most intriguing[1].

In this paper we explore some of the issues that arise when such coordination is achieved through acoustic interaction. The motivation behind this choice lies in the non-trivial constraints posed by the use of a sound channel which affects all participants, the sound producer included and how these constraints can be met by the adaptive behaviour of *simulated* embodied agents controlled by time-continuous, recurrent neural networks, [1]. Agents are evolved using a genetic algorithm as a search technique so that when placed on a flat arena they will approach one another and try to remain proximate for the longest time possible by means of noisy acoustic interaction. We will show how the resulting behaviour makes sense only from the perspective of the whole embodied agent, and how such behaviour is so integrated that perturbation of any component (like self-hearing) is enough for the whole behaviour to collapse. Finally, we will show how coordination is achieved by means of a dynamic and structural congruence between the interacting agents by contrasting how agents behave individually and in pairs.

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[1] E.g., sustained duetting in *Laniarius aethiopicus* and other East African birds, [3]

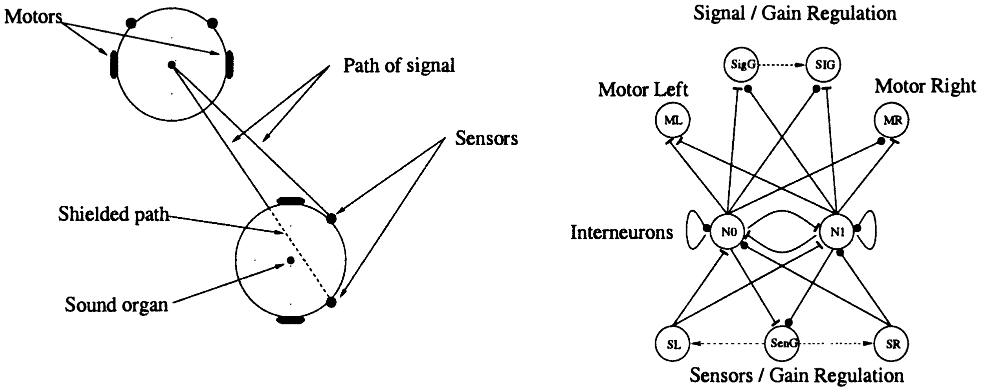

Figure 1: Agent's body, and neural network (only two inter-neurons shown).

## 2 Model

Each agent is modelled as a circular body with two diametrically opposed motors and two sound sensors symmetrically placed at 45 degrees to the motors (see Figure 1). Motors can drive the agent backwards and forwards in a 2-D unstructured and unlimited arena where they move freely except when they collide with each other[2]. A sound organ is located at the center of the body. Sound is *modelled* as an instantaneous, additive field of single frequency and time-varying intensity which decreases with the square of the distance from the source. The sound organ regulates the intensity of the sound produced. Since the task the agents must perform involves some sort of spatial discrimination this must be provided by the relative activity of the sensors. These are physically separated so that in general they will be influenced by different external intensities, however this difference provides poor discrimination especially if we add background noise. In many natural cases spatial discrimination involves the attenuation of intensity as sound travels *through the body* which is linked to the angular movement of the agent, except in the case of sound produced by itself[3]. This "self-shielding" mechanism is modelled as a linear attenuation without diffusion proportional to the distance travelled by the signal within the body. If there is a direct line between sensor and source the perceived intensity is 100 % of the intensity (at that time and position), otherwise the intensity is reduced up to a minimum of 10 % in the case when the sensor is directly opposed to the external sound source (see Figure 1).

A 4-node, fully recurrent, continuous inter-neuron network was used as the agent's controller[4]. Dynamical neural networks have proven to be a powerful tool for studying adaptive behaviour, [1], especially when dealing with time

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[2] Collisions are modelled as point elastic: no energy loss and no angular effects.

[3] Other natural mechanisms involve differences in time of arrival to the ears, (effective at low frequencies, $< 1400 Hz$ in humans) or specific combinations of frequency filtering and delaying. At this early stage these remain beyond the scope of our model.

[4] For reasons of space, full details on parameter ranges will be available, along with the simulation code, from the following webpage: `http://www.cogs.susx.ac.uk/users/ezequiel/coord/coord.html`.

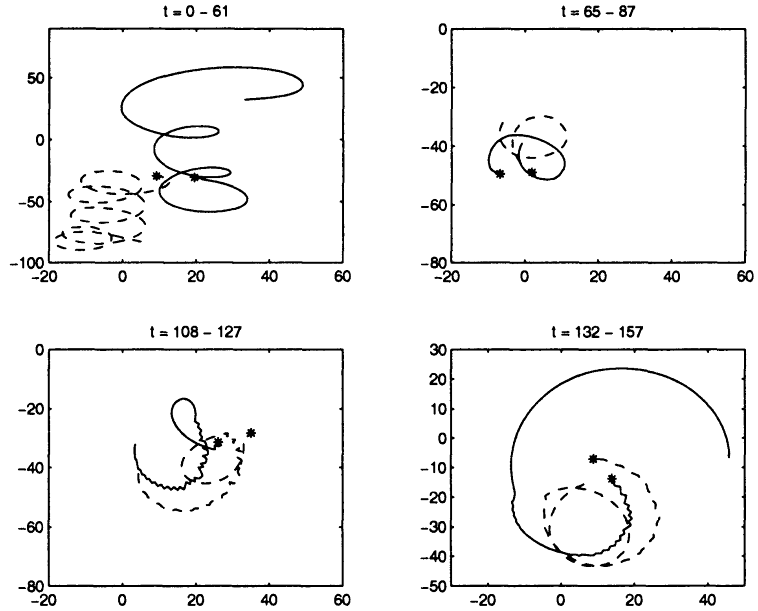

Figure 2: Spatial trajectories of interacting agents (bodies not shown).

constraints becomes an essential part of adaptation. Sensors and effectors are also constituted by neurons which connect with all 4 nodes in the inter-neuron network. Inter-neurons and effectors neurons obey the following law:

$$\tau_i \dot{y}_i = -y_i + \sum_j w_{ji} z_j; \qquad z_j = logistic(y_j + b_j).$$

while sensory neurons obey: $\tau_i \dot{y}_i = -y_i + I_i$, where $y_i$ represents the cell potential, $\tau_i$ the decay constant, $b_i$ the activation threshold, $z_i$ the firing frequency, $w_{ij}$ the strength of synaptic connection from node $i$ to node $j$ and $I_i$ the incoming current into sensory neuron. In some cases sensors are directly regulated by their participation in the network dynamics (i.e. by incoming synapses). We chose not to model direct synapses from the inter-neuron network into the sensory networks, and instead we added an effector that directly regulates the sensory gain. This is done in the hope that it will facilitate analysis. The gain of effectors can be regulated as well. In all cases presented here we have used only two regulatory neurons, one for regulating the gain of both sensors, and another one for regulating the gain of the sound organ. Gain regulation gives a minimal bodily plasticity. There is no other form of structural change.

In order to constraint sound production to realistic behaviours we allow sensors to "burn up" if the cell potential of the sensory neurons exceeds certain limits due to intense sounds. A burnt sensor results in zero fitness for the agent in that run. Resulting structures can be viewed as approaching natural cases where viable behavioural (and evolutionary) trajectories are characterized by a certain equilibrium between the autonomy of the nervous system and the autonomy of the individual cells.

A rank based selection genetic algorithm was used as a search technique

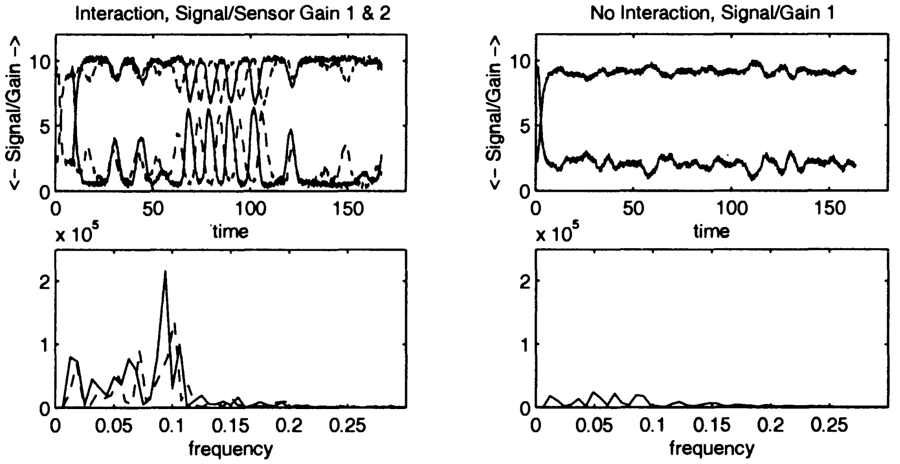

Figure 3: Signals, sensors gains (top) and frequencies spectra (bottom).

with a fixed population of 90 agents evolving for up to 1000 generations. Each agent was selected an average of ten times (five guaranteed) to play with a randomly chosen different agent in the population which was introduced in the arena at a random time after the first one. Fitness values were averaged over all the trials. Fitness was allocated in terms of how much the agents approached each other at the end of the run, and how much time they spent within a distance of 4 body radii of each other.

All parameters (weights, gains and biases) were encoded in a real-valued vector of fixed dimension. Each component specified a parameter by a value in the interval [0,1], (later scaled appropriately). An agent with $N$ inter-neurons and $N_{SE}$ sensors/effectors would have a genome size of $(N + N_{SE})(N + 2)$. Symmetry between left and right hemispheres was enforced only for biases and gains but not for weights and some of the gain parameters were directly regulated by the agent (see above), so the resulting genome size was usually less than the above quantity. No crossover operator was used, and mutation consisted in perturbing the genome vector in a random direction with probability $\mu = 0.005$ by a distance chosen uniformly in the interval [0,1].

# 3 Integrated behaviour and coordination

Different approaching behaviours evolved successfully after a few hundred generations in separate runs; we will report on the most common of them. This behaviour involves strong angular movement during the initial phase (see Figure 2, top left), which is an effective way of actively using the mechanism of self-shielding to produce differences of integrated activity between the two sensors. Less "dynamic" approaching strategies would, after initial orientation, fail to discriminate further because attenuation would be similar for both sensors. Signals are produced in an oscillatory pattern, which is coordinated with the sensor regulation so that sensory gain is reduced for high intensities (Figure 3, top left). Signalling behavior does not only perform the function of a beacon, but it is fully integrated into the search behaviour of the signal producer as can be seen in the fact that if we perturb the ability of *self*-hearing while leaving the rest intact, search behaviour collapses and agents rotate on the spot[5].

If we extend the interaction time, agents perform a behaviour similar to a dance alternating between "leader" and "follower" (Figure 2). Figure 3, top left, shows periods of entrainment between the signals in an anti-phase mode resembling turn-taking, and the Fourier transform of the signals (bottom). Coordination patterns are not permanent, but can be lost and regained. Although both agents were taken from a same evolved population their structures are not identical. If we place each agent on its own in the arena they will wander trying to pick up some external signal, however, we observe (Figure 3 right) that the "natural" signalling behavior is both very different from the interactive case and also between the agents (not shown). The result of ongoing mutual interaction is the triggering of internal structural and dynamic changes (particularly during transients) that drive the agents to possess congruent characteristics manifested in the entrainment of signals. As a consequence of these changes agents become "tuned" to one another thus allowing coordination to be sustained for long periods, and to be regained if it is briefly lost.

In order to verify that a period of un-coordinated and transient coupling is required before the achievement of coordination, an immobile sound generator (beacon) was placed in the arena. This beacon imitates the long term signalling behaviour of the coordinating agents. If we place an agent in the arena and activate the beacon after a while, we would expect the agent to coordinate its signals with the beacon's. It does not happen. The agent signals sporadically with long periods of "silence" (although it approaches the beacon). Since the beacon is non-plastic, it is clear that it cannot actually *inter*act with the agent during the transients when attunement occurs, (the different long-term dynamics are shown in Figure 4 for two inter-neurons for one agent).

## 4 Discussion

These experiments help us to explore the biological significance of social coordination through acoustic interaction. There is no trivial functional decomposition of behaviour into *social* and *non-social* categories: emitted sound is used both to regulate movement and to signal spatial position and movement is used both to discriminate internal signals from external sources and to approach the latter. Nor is there any trivial way of separating one agent's behaviour from the other's once certain degree of structural congruence has been obtained through sustained interaction. After an initial transient, the whole agent-agent sys-

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[5] Note that we are concerned with acoustic interactions in which self-stimulation is *unavoidable*. It is possible to evolve structures that will perform the approaching behaviour without self-hearing but this is not the question we ask here. In general, if we perturb self-hearing overall behaviour will change, it is not clear that it will change so dramatically even for small perturbations (like a 5 % reduction in self-hearing), thus proving the difficulty of trying to functionally decompose behaviour into purely social/non-social categories. Signalling behaviour plays a role in both.

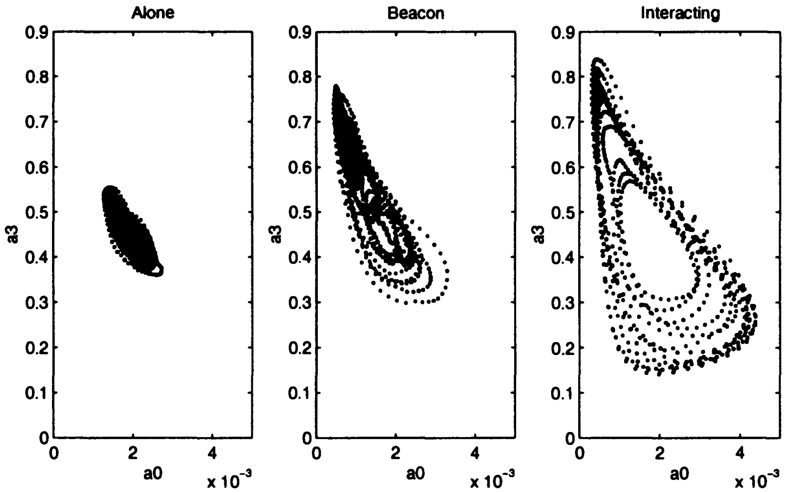

Figure 4: Attractor dynamics for a given agent when acting alone, in the presence of a periodic beacon, and interacting.

tem attains a state of coherence which is manifested in the fact that different "natural" patterns in the isolated agents are replaced by a single coordinated behaviour. Without such transients agents produce different behaviours even in the presence of a beacon that imitates their signalling patterns.

Since behavioural coordination lies at the basis of all animal communication (human language included) exploring its mechanisms becomes a significant task if we are interested in understanding social behaviour. Questions like what causes a pattern of sustained interaction to break off, how a history of interaction affects future encounters, what counts as an invariant during interaction, etc., need further exploration. We think that the use of simple models such as this one is a promising route.

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