Behavioral Coordination, Structural Congruence and Entrainment in a Simulation of Acoustically Coupled Agents.

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Social coordination is studied in a simulated model of autonomous embodied agents that interact acoustically. Theoretical concepts concerning social behavior are presented from a systemic perspective and their usefulness is evaluated in interpreting the results obtained. Two agents moving in an unstructured arena must locate each other, and remain within a short distance of one another for as long as possible using noisy continuous acoustic interaction. Evolved dynamical recurrent neural networks are used as the control architecture. Acoustic coupling poses nontrivial problems like discriminating 'self' from 'non-self' and structuring production of signals in time so as to minimize interference. Detailed observation of the most frequently evolved behavioral strategy shows that interacting agents perform rhythmic signals leading to the coordination of movement. During coordination, signals become entrained in an anti-phase mode that resembles turn-taking. Perturbation techniques show that signalling behavior not only performs an external function, but it is also integrated into the movement of the producing agent, thus showing the difficulty of separating behavior into social and non-social classes. Structural congruence between agents is shown by exploring internal dynamics as well as the response of single agents in the presence of signalling beacons that reproduce the signal patterns of the interacting agents. Lack of entrainment with the signals produced by the beacons shows the importance of transient periods of mutual dynamic perturbation wherein agents achieve congruence.

Keywords: Social behavior, embodied autonomous agents, acoustic interaction, coordination, entrainment, structural congruence.

1 INTRODUCTION

In the late forties W. Grey Walter wired a headlamp into the steering circuit of his *Machina speculatrix* that would be turned on while the robot was performing its exploratory behavior and turned off when the robot's photoelectric sensor detected a moderate light, (Holland, 1996, Walter 1950, 1953). Since the natural tendency of these 'turtles' was to explore their environment following a cycloidal path until they detected a source of moderate light, and then move toward it while keeping a certain distance (i.e., avoiding intense light), some fascinating dancing patterns were witnessed when two of them (Elmer and Elsie) were placed on the same floor with all the sources of light switched off except for their own headlamps. A turtle in the exploratory mode would have its headlamp on until its sensors detected the light coming

from its partner. Then the headlamp would go off. If the same thing happened to its partner both turtles would begin a movement toward a source of light that would be extinguished at the next moment, and therefore they would resume exploration, i.e., turning their lights back on, and so on. The turtles would approach and stop intermittently toward each other's flickering headlamps, until the light of one of them would move beyond the range of the other one's sensor and they would 'lose interest'. This simple experiment, explainable in terms of wires, light bulbs and mechanical bodies, poses nontrivial questions about the nature of social behavior. Are Elmer and Elsie acting socially? Would they be if they were endowed with a mechanism that would let them regain their interaction pattern once it was lost? When *is* a behavior social? What exactly do we have in mind when we say that social behavior is fundamental for understanding the evolu-

tion of intelligence? Many inheritors of Walter's tradition still find these questions pressing.

Our goal in this paper is to address some of these issues theoretically, and to present a model partially inspired by Walter's interacting turtles in which we can explore the value of the theoretical concepts introduced. More specifically, we set out to explore, by means of simulations, some of the coherent behavioral patterns that can arise from sustained interaction between embodied autonomous systems through an acoustic medium. We will show that this coherence can be explained in terms of the systemic concept of *structural congruence*, the attainment of which is to be expected under a variety of circumstances.

The choice of sound as a means of interaction in our model is not incidental. Acoustic interactions are conspicuous in nature, and some of their physical features, as well as those corresponding to auditory perception, make this 'channel' a particularly interesting one from the point of view of adaptive behavior. For instance, organisms using sound as a means of achieving behavioral coordination must face nontrivial problems such as distinguishing their own production from those of others and avoiding mutual interference of signals[1]. Problems like these did not arise in the way Elmer and Elsie were coupled.

Our approach differs from some recent models addressing the evolution of communication (DiPaolo, 1998; MacLennan, 1994; Werner, 1991) in that our interest is focused more on behavioral issues rather than on evolutionary ones. In order to make positive contributions to evolutionary questions these models must assume too much in terms of how the interactions between individuals are structured to be useful for understanding purely behavioral questions. In contrast, we will aim at making fewer assumptions about the nature of the interaction and the behavioral building blocks that we incorporate into our agents.

A related type of work using simulations explores issues like the evolution of symbolic systems and lexicon formation. These models often made very strong assumptions about what communication is and about the requirements of individual competence regarding categorization and 'naming' of categories. We believe that a much lower level understanding of social behavior must be achieved from the perspective of embodied autonomous systems, before we may hope to explain *behaviors* such as 'giving a name to a category'

or 'referring to an external object'. Thus our work will be more related to work done using real robots in social interaction, (Billard, 1997; Dautenhahn, 1995; Mataric, 1995 and others), the aim of which can sometimes be understood as double: to address questions about the nature of social behavior (for instance, the relation between social skills and individual competence) as well as to build socially intelligent robots that can coordinate their actions in the performance of a complex task. We will restrict ourselves only to the former aim. This is why we specifically address means of interaction that can be found in nature, such as acoustic signals, their physical implications and the problems they pose. Our concern, therefore, lies more on the scientific side: we want to test the usefulness of our methodology in understanding natural social behavior. Any knowledge or inspiration we may obtain about engineering issues will be considered as a plus.

The following section discusses some issues regarding social behavior from the point of view of coupling between autonomous systems. In section 3 we identify some basic physical aspects of sound as a channel of interaction and in section 4 we present a natural example of complex acoustic coupling. Section 5 discusses the scope and methods used for building and studying the model presented in section 6. The rest of the paper presents and discusses the results obtained.

2 A SYSTEMIC PERSPECTIVE ON SOCIAL BEHAVIOR

A dynamical systems approach to the study of adaptive behavior (Beer, 1995) can be taken as opposing any type of functional explanation and favoring only purely operational descriptions in terms of attractors, potential wells, and couplings between complex systems, (see Faith 1997). This may be too narrow a point of view. The purpose of an operational explanation is not necessarily to act as a replacement of a functional one, but rather to act as a constraint to the possible functional interpretations that we may need to provide for pragmatic purposes. For this reason, it is a worthwhile enterprise to try to identify such operational constraints using dynamical systems theory and other systemic concepts even if a complete dynamical description cannot be given. This is what we intend to do very briefly in this section for some

general issues related to social behavior.

When we think about social behavior, the first thing that comes to mind is some notion of coordinated activity between two or more autonomous entities. In order to understand what we mean by this, we must describe the meaning of autonomy, interaction and coordination.

A possible definition of *autonomy* in non-functional terms is given by Varela (1979, p. 55). A system is autonomous if its organization has the property of being operationally closed. This does not mean that the system does not interact with its external environment. It means that its organization is constituted by a network of internal processes, and that the operation of this network is sufficient for those constituting processes to be generated and sustained (constituted) without any of them being driven from outside the system. At the same time the *identity* of the system is defined as long as it remains operationally closed, (Varela 1979, p.57).

What sort of relation can an autonomous system have with its environment in order to remain *autonomous?* It is clear that as soon as this relation is one where the closure of the internal organization of the system is disrupted from the outside, autonomy will be almost certainly lost[2]. Preservation of autonomy divides the space of possible interactions into those that are allowed and those that are not, and this space is obviously contingent on the present state of the system. Allowed interactions will be manifested as perturbations to the system that do not break its operational closure, and not as instructing the dynamical path that the system will follow. A process, whereby the system interacting with its environment undergoes a succession of allowed perturbations of this kind without losing its autonomy, is called a process of *structural coupling*, (Maturana & Varela, 1980)[3].

Structural coupling occurs between a system and its medium, which may include other autonomous systems, in which case we speak of an *interaction*. However, mere interaction between autonomous entities does not seem to be enough to describe the resulting behavior as social even if it happens to have an adaptive function. There is something lacking in two animals just bumping into each other while trying to escape from a predator to call that a social interaction. What we are looking for is a concept that will allow us to describe the complex patterns of social behavior

that we observe in humans and other species. This is the idea of *coordination*[4].

Coordination is a subtle concept. In one interpretation, it involves the fact that many organisms can have a complex behavioral repertoire that allows what, for an observer, seems to be a simultaneous instantiation of different behaviors, (for instance, walking and talking in humans). When two or more organisms are interacting only a part of this behavioral space may be occupied directly in the interactive activity. However, if we do observe a coherence between behaviors *not* involved directly in the interaction, then we are in the presence of coordination, (Maturana & Varela, 1980, p. 27 - 28). Another, equally valid, interpretation would not require that the different behavioral domains, the one in which the interaction occurs and the one in which coordination is elicited, be simultaneously instantiated, but coherence in the latter still needs to show dependency on the outcome of the interactive activity in the former.

Coherence means an observable agreement between behaviors of different organisms, from simple instances of synchronized activity or other forms of temporal consistency (such as the group response to an alarm call) to more complex cases, such as the patterns shown by members of a wolf pack when hunting large prey, or the approaching behavior and maintenance of the pair bond in monogamous species of tropical birds by means of antiphonal duetting (see section 4). We may ask why should there be any relation between the coordinated behavior (in the last example, song synchronization and approaching) and the interaction (singing), unless both organisms were somehow congruent enough in structural terms so that (a) the coordinated behavior is *possible* for both of them, and (b) their structures are such that the coordinated behavior is somehow related operationally to the fact that they are undergoing a specific pattern of interaction. See figure 1 where the state of the behavioral domains of two organisms in interactions is shown through time. Coherence is depicted by congruence in the form of the diagrams which represent the individual domains of behaviors. Interaction is shown as a single activity in which both organism engage (top). Coordination is shown as additional coherence which depends (operationally) on the existence of interaction (bottom).

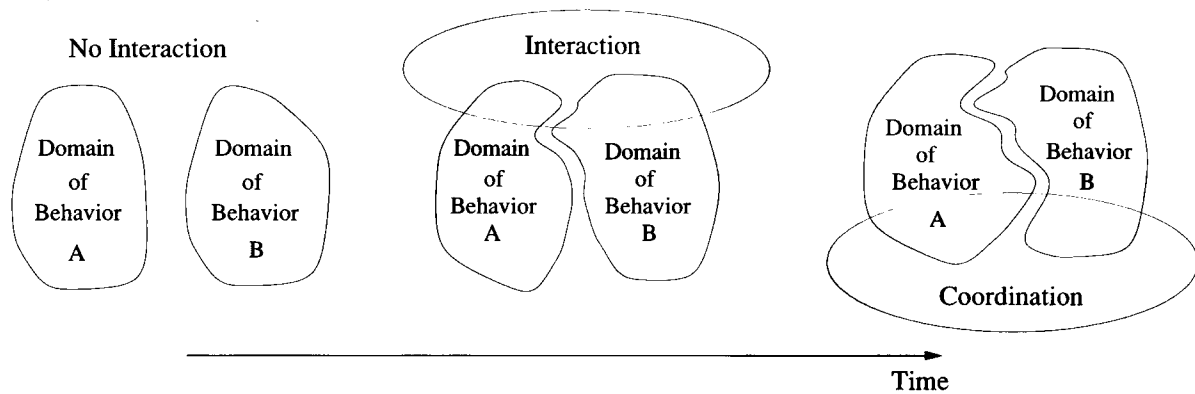Each perturbation that an autonomous system

Figure 1. Illustration of the concept of coordination.

undergoes during structural coupling may induce changes in its structure, and some of these changes may be plastic. Plastic changes occur when the structure of a system undergoes an alteration from which it does not recover within the same time-scale with which the change happened but with a larger one. Clearly, some of these changes may be permanent.

As a special case of structural coupling, coordinated interactions between organisms may also induce such changes. The process of mutual coordination is, at the same time, a process of mutual selection of plastic changes in their respective structures, so that not only the ensuing behaviors result in a coherent pattern but also the corresponding structural changes may show some degree of coherence. The resulting relation between the structures of the coupled systems is known as *structural congruence*, and it is to be found particularly between organisms that engage in interaction repeatedly and recursively. Sustained patterns of interaction tend to become embodied in the participants in the form of a history of structural changes during each individual's lifetime. As a result, subsequent encounters may be affected either in ways that facilitate the reproduction of the pattern of interaction, or in ways that do not. If facilitation of future encounters is the result of certain patterns of interaction, it is clear that those patterns will tend to be conserved. For certain plastic systems, this process could constitute the basis of social affinity, (an example is presented in section 4).

Of special interest is the case where structural con-

gruence is achieved between 'unevenly plastic' organisms, as in the case of parent/offspring social interaction. If structural congruence is understood as the meeting of two distinct, though not completely dissimilar, structures in some common ground, it is clear that those interaction patterns that facilitate their own reproduction by inducing structural changes will tend to produce what for an observer would look like a *directed* structural change in the more plastic organism towards a structure that is congruent with the less plastic organism. This phenomenon, and its opposition (the structural 'rejection' of patterns that make their own reproduction difficult), could be used as an operational basis for explaining many instances of social learning.

We should stress that there is nothing magical about coordination. Consider one of its possible manifestation in rhythmic forms of behavior: entrainment or synchrony. There is a growing literature on synchronization of coupled oscillators in biology and chemistry (see Winfree, 1980; Kuramoto, 1984 for 'classic' introductions). The striking fact is that under a vast set of conditions synchronization is the expected result. Additionally, coordination in rhythmic behavior is not just manifested in phase-locking, but more remarkably in tendencies to correct phase deviations. Kelso calls this phenomenon *relative coordination* after von Holst, (Kelso, 1995). Entrained behavior may be difficult to maintain in the case where the interacting systems are not identical. However, the systems, under certain conditions, may manage to

compensate for phase slippage. Such is the case of an adult and child walking together at the same speed in spite of differences in their individual 'natural' speeds. Even if we were able to provide a fully operational description, in many natural cases we would tend to *interpret* this compensating coordination as if the systems involved had an 'interest' in maintaining certain types of interaction. Something that, from available descriptions, Walter did not find in the behavior of Elmer and Elsie.

3 ACOUSTIC COUPLING

The use of sound is conspicuous in the animal world where it is associated with a variety of behaviors, particularly, but not exclusively, with social behaviors. The following list describes some of the relevant physical characteristics of interactions that rely on an auditory channel. In general, these features should be taken as givens whenever such interactions are present.

Finite locality and directionality. Sound intensity decays with the square of the distance to the source and it does not linger after it has been produced. It is also affected by other factors like wind direction and speed as well as the acoustics and filtering characteristics of the environment. Perception of sound is therefore a reliable measure of proximity at the moment of perception. Due to this feature the most basic behaviors relying on (voluntary and involuntary) production of sounds are related to localization functions (detection of predator/prey or potential mates, etc.).

Localizability. Binaural perception allows for spatial discrimination of the sound source. The mechanisms involved are varied, but rely mainly on temporal and intensity differences between the sound perceived in each ear. Differences in time of arrival of an acoustic signal can be used to pinpoint its source if the duration is short. For continuous tones, this mechanism is only effective at low frequencies (less than 1400 Hz in humans), since it relies on a discrimination of the wave phase (see Kandel, Schwartz, & Jessell, 1991; Rozenweig, 1954; King & Carlile, 1995). For higher frequencies this information becomes ambiguous as more than one cycle may occur within the distance that separates the ears. Another mechanism provides discrimination based on differences of intensities between the sound perceived by each ear. Here, the actual difference due to intensity decay of the sound wave is not as important as the shadowing effects of the relative angular position of the head with respect to the source. For short wavelengths the head casts a considerable shadow in the travelling sound waves. In this case, differences in intensity are much more accentuated if the body comes between the source and one of the ears. In humans this difference can reach up to 20 dB for a continuous tone of 6000 Hz (Feddersen, Sandel, Teas, & Jeffress, 1957). This mechanism facilitates active discrimination involving movement of the body as was first observed by Venturi's experiments in the 1790's (see Rozenweig, 1961)[5].

Sound affects many individuals at the same time. Although sound production can be directed, in the general case sound is broadcast within its local range, and can affect more that one individual organism. Acoustic signals necessarily influence the originator unless specific mechanisms prevent this from happening (e.g., synchronized sensory inhibition in bats during emission periods in echolocation). The role of this latter feature must not be downplayed. A discrimination between externally and internally generated sound (when necessary) poses the nontrivial problem of distinguishing between 'self' and 'non-self.'

Sound is continuous. Another feature that should be considered as a given in acoustic interactions is the fact that sound signals are inherently continuous, although they can be made discrete by controlling the time structure of their production. In combination with the above, this feature introduces the problem of how interactions are structured temporally and with respect to the number of participants to avoid interference between simultaneous productions. One to one interaction and turn-taking patterns require a certain degree of behavioral coordination, which, in some cases, may result from acoustic interaction itself, but they may also involve different sorts of physical coupling such as body movements, touch, direction of gaze, etc. Purely gestural interactions, in contrast, may take place with a certain degree of simultaneity.

So far, auditory interactions have not received the attention they deserve, especially from those in the adaptive behavior community engaged in the study of social behavior. For instance, many studies concerned with the evolution of communication (Di Paolo, 1997; MacLennan & Burghardt, 1994; Werner &

Dyer, 1991, and others) already assume discreteness, turn-taking or some other structured regulation of participation as the basic substrate upon which communicative behaviors evolve. However, to be fair, none of these models is aimed at addressing the continuous/discrete transition or the problem of how participants structure a pattern of interaction in time. Another common assumption is the one-to-one nature of interaction which, as we have seen, is not a given in the physical properties of the sound channel. Some of these assumptions have been also criticized by Saunders and Pollack (1996). They present a model of communication over continuous channels where many emitters can affect at the same time a given agent in varying degree depending on the corresponding distances. The physical features of their signalling channels are inspired by acoustic interaction, however they explicitly exclude the effects of self-stimulation and its associated problems.

At this stage, our model does not intend to address all these issues. For instance, we will address the issue of self-stimulation over a continuous channel, but we will restrict ourselves to pairwise interactions which is in itself a severe limitation. The motive for this restriction, apart from some technical difficulties, is the (reasonable but not entirely justified) suspicion that this will be a useful preliminary step for understanding more complex models with many agents interacting simultaneously.

4 AN EXAMPLE OF COORDINATION THROUGH ACOUSTIC INTERACTIONS

In order to illustrate the concepts introduced in the preceding sections we will briefly describe a natural case of social coordination and structural congruence via an acoustic channel[6].

In many monogamous species of tropical birds, singing is not limited to the male but both male and female sing together, in some cases performing antiphonal duets, i.e., alternation of different note patterns (Farabaugh, 1982)[7]. Antiphonal duetting has been studied in a number of East African species, particularly in certain shrikes (*Laniarius*) (Thorpe, 1972; Hooker & Hooker, 1969; Wickler & Seibt, 1979). One of these species, the bou-bou shrike (*Laniarius aethiopicus*) lives in dense forests and produces a flute-like sound. Duets are constituted by patterns of notes

so precisely alternated that they can be confused with the performance of a single bird. Each bird has its own part and they are not interchangeable, although some rare records have been made of birds that completed their partner's part when alone. Each pair has a variety of different patterns, some of which are exclusively their own. Performance of duets can serve both the purpose of localization and demarcation of territory within the dense foliage as well as maintenance of the pair bond (Wickler, 1980; Wickler & Seibt, 1980). Hooker and Hooker (1969) observe that there is no signal other than the production of the first note for the duet to start, and that the tendency to respond can be very strong sometimes forcing the interruption of preening or a response through a beakful of live food. They also report the lack of observation of periods of 'practicing' in young shrikes which suggests that the particular features of the duetting pattern are acquired through interaction within the pair.

Duetting thus serves as an example of a type of acoustic interaction which not only requires a high degree of coordination in itself but can also coordinate other behaviors, such as approaching. The fact that specific pairs of duetting birds develop a repertoire that reflects their own particular history of interactions, and, partly as a consequence of this, they will pair for life, can be taken as evidence of the role of acoustic coupling in the achievement of ontogenetic structural congruence.

5 METHOD

The rest of the paper will describe a simulation model which will help us explore some aspects of the concepts discussed above. Inspired by the example of duetting birds we will introduce a simulation of embodied agents that can interact through an acoustic channel. We mentioned that duetting in shrikes can elicit localization behavior in dense foliage. Based on this observation we propose to study how mobile agents that cannot use visual clues can approach each other by the exclusive use of acoustic interaction (i.e., signal production and phonotactic behavior). As we explained in section 3, there are some basic assumptions in this type of coupling that have to be made from the start, such as continuity and locality of the sound channel.

We will use continuous time recurrent neural net-

works as the internal architecture of the agents since we want our agents to produce behaviors that are continuous in time and this type of network has proven adequate for generating such behaviors. In the spirit of reducing the initial set of assumptions we will not build the agents directly, although we will specify certain parameters (such as body size) as constant and given[8]. An evolutionary search algorithm will be used to explore the space of possible structures.

A word must be said about the use of a genetic algorithm (GA) in the context of this work. Since we are not concerned with providing an evolutionary scenario wherein the behaviors under study are a plausible outcome, we will restrict our application of evolutionary techniques purely to the task of searching a complex design space. Therefore, we will not derive any conclusions about the likelihood of evolutionary histories that may lead to such behaviors. Examples of natural organisms that interact through an acoustic channel are sufficiently abundant to provide evidence that such cases are not evolutionarily implausible. Instead, plausibility restrictions are imposed on the constraints that provide the context of the search process both in the form of the physical laws fed into our model, and in the form of performance evaluators for viable structures and behaviors.

It is fair, then, to inquire about the reasons for using a GA instead of other equally efficient search techniques. Given the number of successful cases where this method has been applied in recent years both in simulated agents and actual robots, and at the interface between the two (see Beer & Gallagher, 1992; Harvey, Husbands, Cliff, Thompson, & Jakobi, 1997; Jakobi, 1997, and others), one reason for using a GA may be attributed simply to its proven adequacy for similar search tasks.

The study of the resulting behaviors will follow more traditional techniques of observation and analysis of interaction patterns and internal dynamics. We will also use perturbation and disruption of normal modes of behavior in order to try to understand how such behavior is integrated.

6 THE MODEL

6.1 Sound

Sound is modelled as an instantaneous, additive field

of single frequency with time-varying intensity which decreases with the square of the distance from the source. At this stage we will explicitly ignore effects of time-delays and differences in frequencies of sound production, (i.e., no Doppler effect, differential filtering, etc.). This coarseness of modelling will fit with the mechanism for spatial discrimination allowed in the model and described below.

6.2 Bodies

Each agent is modelled as a circular body of radius $R_0 = 4$ with two diametrically opposed motors and two sound sensors symmetrically placed at 45 degrees to the motors (see figure 2). The position of the sensors was chosen in order to introduce a back/front asymmetry (although which is which is not specified) because we want to be able to evaluate angular effects, and coordination of physical orientation. A sound organ is located at the center of the body, and regulates the intensity of the sound produced by the agent. The motors can drive the agent backwards and forwards in a 2-D unstructured and unlimited arena. In this simple model, we may think of the agents as a rigid body, small in size and having a very small mass, so that the motor output is the tangential velocity at the point of the body where the motor is located. The translational movement of the whole agent is calculated using the velocity of its center of mass (the vectorial average of the motor velocities), and the rotational movement by calculating the angular speed (the difference of the tangential velocities divided by the body diameter). There is no inertial resistance to either form of movement.

Agents move freely in the arena except when they collide with each other. Collisions are modelled as point elastic, i.e., no energy loss and no effect in the angular velocity of the bodies. While undergoing a collision, an agent moves in a direction which may not be the one specified by its motor output, but which corresponds to a displacement that conserves the momentum of the whole system. The bodies of both agents are taken as identical so that the result of an elastic collision is the instantaneous 'exchange' of the velocity vectors at the center of mass. However, due to the lack of inertia, agents recover control of their movement immediately after the collision. The body circumference is taken as frictionless so that the angu-
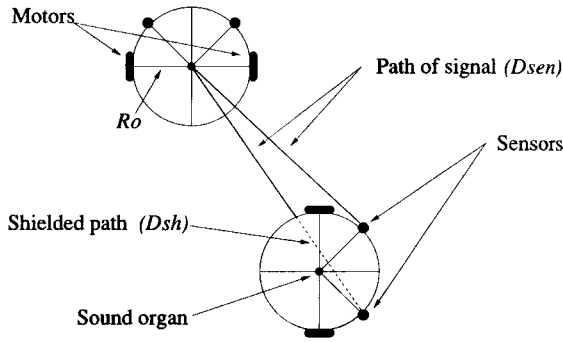
Figure 2. Body of agents and paths of acoustic signals.

lar velocities do not change during collisions.[9]

Since the task that 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 their activity will be influenced by different external intensities, however such a difference provides poor discrimination especially if background noise is added. A natural
mechanism, as we mentioned in section 3, involves the attenuation of intensity as high-frequency sound is shadowed by the body. The degree of attenuation is linked to the angular position and movement of the agent except in the case of sound produced by itself. This 'self-shadowing' mechanism is modelled as a linear attenuation without refraction proportional to the distance travelled by the signal within the body, D_{sh}. This distance is given by:

$$D_{sh} = D_{sen}(1 - A), \quad 0 \le A < 1,$$

$$A = \frac{D^2 - R_0^2}{D_{sen}^2}$$

where D_{sen} is the distance between the source and the sensor, and D is the distance between the source and the center of the body. If $A \ge 1$, there is a direct line between source and sensor, and so $D_{sh} = 0$, (for $A = 1$ the sensor, the center of the body and the external source form a right triangle). The maximum value of D_{sh} is given when the sensor is directly opposed to the external source ($D_{sh} = 2 R_0$). The attenuated signal is calculated by first calculating the intensity of the signal at the position of the sensor in the usual way (i.e.,

applying the inverse square law without attenuation) and then multiplying by an attenuating factor which goes linearly from 1 when $D_{sh} = 0$ to 0.1 when $D_{sh} = 2 R_0$. The process is repeated for the other sensor.

The agent's controller is composed of a network of four dynamic inter-neurons and an arrangement of sensors and effectors each one controlled by one neuron. The inter-neuron network is fully connected (including self-connections). Additionally, each inter-neuron receives one incoming synapse from each sensory node (of which there are only one for each auditory sensor) and each effector node (one for each motor, one for signal production and two gain regulators as detailed below) receives one incoming synapse from each inter-neuron. There are no direct connections between sensors and effectors. This kind of dynamical neural networks can serve as an adequate basis for a fully embodied operationally closed mechanism, and so they are a good tool for studying adaptive behavior in simple autonomous agents, as some successful cases have shown (Beer & Gallagher, 1992; Beer, 1996, and others). This is especially so when time constraints become an essential part of adaptation. Inter-neurons and effector neurons obey the following law:

$$\tau_i \dot{y}_i = -y_i + \sum_j w_{ji} z_j; \quad z_j = \frac{1}{1 + \exp[-(y_j + b_j)]}.$$

and sensory neurons obey:

$$\tau_i \dot{y}_i = -y_i + I_i,$$

where, using terms derived from an analogy with real neurons, y_i represents the cell potential, τ_i the decay constant, b_i the bias, z_i the firing frequency, w_{ij} the strength of synaptic connection from node i to node j and I_i the degree of sensory perturbation on the sensory node (modelled here as an incoming current).

In some models, sensors can be 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 neurons and instead we added an effector that directly regulates the sensory gain in a multiplicative way. Such regulation allows the agent to have the possibility of extra control on sensory activity. The gain of

effectors can be regulated as well. In all cases presented here we have used only two regulating neurons, one for the gain of both auditory sensors (in a symmetric way), and another one for the gain of the sound production organ. In each sensor a transduction step occurs which transforms external stimuli into a degree of perturbation (incoming current). Analogously for effectors, a transduction step transforms the neuron firing frequency into motor output. These transduction steps are simply modelled as linear scalings (i.e., a multiplication of the firing rate by a gain). In sensors or effectors with regulated gain the activation of the regulating neuron defines in each time step the scaling value by transforming linearly its own firing rate (between 0 and 1) into the gain value (see next section for ranges).

In order to constrain the production of sound to a realistic behavior we allow neurons to 'burn up' if the cell potential exceeds certain limits due to intense stimulation. In sensory neurons this may happen in the presence of intense sounds. In real auditory systems the destruction of hair cells occurs for mechanical reasons and not due to intense incoming currents into the nerve cells. This is the reason for stressing that the meaning of I_i in this model should be taken as the degree of perturbation or stimulation to the sensory cell and not necessarily as a literal current. The resulting neuronal structures can be seen as approaching natural cases where viable behavioral trajectories are characterized by a certain equilibrium between the autonomy of the nervous system and the autonomy of the individual cells. This mechanism also provides additional significance to the sort of interactions that an autonomous agent may engage in. Evolved agents should be expected to 'take care' regarding the intensity of their own sound production and/or use their sensory gain regulation accordingly.

6.3 Genetic Algorithm

A form of rank based selection genetic algorithm was used as a search technique with a fixed population of 90 agents evolving for up to 1000 generations, (after a few hundred generations highly fit individuals evolved). Each agent was selected an average of ten times to play with a different agent in the population which was introduced in the arena at a random time after the first one. This delay is introduced in order to

to avoid cases where agents undergo similar dynamics in an artifactual way simply because they start their operation at the same instant and from similar initial conditions[10]. The second agent was placed at a random distance no smaller that 50 units from the current position of the first agent. The initial state of the agents was reset at the start of each trial; the cell potential of each neuron y_i was set to a randomly chosen small value taken uniformly from the interval [-0.1,0.1].

Fitness values were averaged over all the trials. Fitness was allocated in terms of how much the agents have approached each other at the end of the run, $(F_A = 1 - D_{Final}/D_{Initial})$, and what proportion of the interaction time they have spent within a distance of 4 body radii of each other (F_D). Additionally, the weighted sum of these proportions was modulated by a mild exponential term that decreases with the integrated energy used. This was done in order to compensate for the lack of an adequate model of energy consumption. Agents making excessive use of motors were penalized very mildly. The individual fitness F for a given trial (usually lasting 200 time steps[11]) can be expressed as:

$$F = (a_d F_D + a_a F_A)\exp(-a_e\int_{t_i}^{t_f}\sqrt{V_R^2 + V_L^2}\,dt,$$

where $a_d = 0.25$ and $a_a = 0.75$ are the weighting factors for the approaching and maintenance of proximity tasks respectively, $a_e = 0.005$ scales the modulation of the exponential and V_R and V_L are the translational speed of the right and left motors respectively. A final factor affecting fitness is cell death (see above). If at the end of the trial run an agent has burnt up one of its sensory or effector neurons, its total fitness in that run is reduced to zero.

Numerical integration of the model was done using the Euler method. This is a second order method and therefore not very accurate, however it is fast enough to study many evolutionary runs. To compensate for the lack of accuracy the integration step was chosen in such a way that similar results were obtained by using an order four Runge-Kutta method[12] with a time step of half the minimum neuronal decay constant. The resulting integration steps for the Euler method used was 0.1 (compare with decay constants below).

All network 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 linearly to the appropriate interval). Transduction gains were chosen from the interval [0.05,10], biases from [-3,3], weights from [-8,8] and decay constants from [0.4,2]. An agent with N inter-neurons and N_{SE} sensors/effectors would have a genome size of $(N + N_{SE})(N + 2) + N_{SE}$. Symmetry between left and right was enforced only for biases and gains but not for weights, and as some of the gain parameters were directly regulated by the agent the resulting genome size was less than the above quantity.

After ranking the population according to fitness the next generation is built by making 2 copies of each individual in the top third of the current population and one copy of each individual in the middle third. No crossover operator was used, and mutation consisted in perturbing the genome vector $\mathbf{G}$ with probability $\mu = 0.005$ in a random direction by adding a normalized vector $\mathbf{p}$ multiplied by a distance m chosen uniformly from the interval [0,1]: $\mathbf{G} \rightarrow \mathbf{G} + m\mathbf{p}$.

Uniform noise was added to all the transduction steps affecting sensors and effectors, (range = 0.1, mean = 0 or 0.05 if the transduction implies a non-negative value). These values of noise are also scaled by the gain of the corresponding sensor/effector.

7 RESULTS

Highly fit agents evolved reliably after a few hundred generations. About 16 different evolutionary searches were run. In 11 of them we observed a same qualitative form of behavioral strategy with small quantitative variations. With less frequency other behavioral strategies were also observed but were not studied thoroughly. We found the most frequent strategy to be interesting enough for a detailed examination. The reported results correspond to a single instance of this strategy, but the same conclusions apply in all 11 instances where the same behaviors were observed.

7.1 Approaching behavior

Agents successfully approach each other when two of them are in the same arena (figure 3 shows an example of the trajectories performed by the agents, and

figure 4 shows the distance between them as a function of time). The structure of the evolved neural network can be seen in figure 5. Only 2 active inter-neurons are 'used' by the agents; the other two have a constant activation of 1 or 0 (not shown). Examination of the sensory activation shows that the signal perceived by one agent at the moment when the other one is placed in the arena is very faint in comparison with the agent's own signal production, and even in comparison with noise levels. Agents engage in a mode of search behavior that relies on the fact that self-shadowing is a mechanism that can be exploited actively by movement with a strong angular component, (figure 3). This helps to discriminate external sounds since perception of an agent's own signal does not depend on its orientation. (Notice also that agents place their sensors 'on the back' with respect to the direction of movement.) Sensors act as leaky integrators and connect differentially to the inter-neurons with similar absolute weights (figure 5, values not shown), which means that the basic strategy would seem to involve rotation while moving, integration of sensed intensities, and evaluation of the difference between left and right sensors (i.e., subtraction of own contribution to sensed sound). This is an efficient way of discriminating faint external sources.

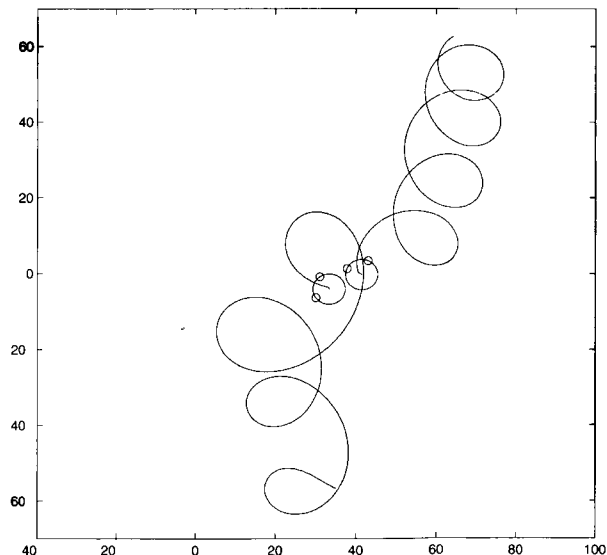However, this is not entirely right. We observe that

Figure 3. Trajectories of approaching agents. The second agent is introduced in the arena at $t=10$.
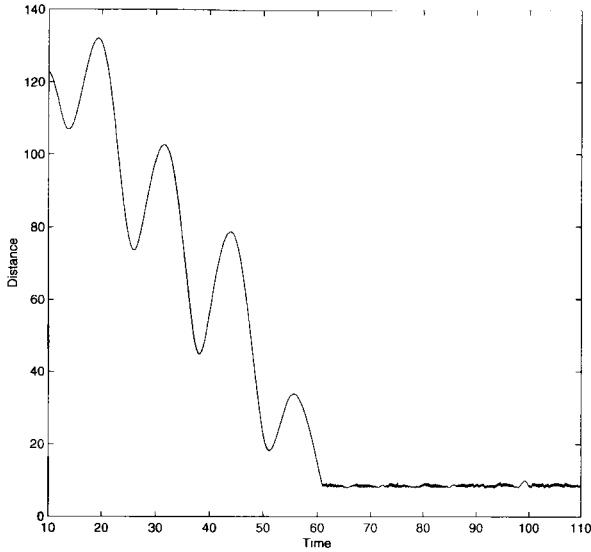
Figure 4. Distance between agents as a function of time corresponding to run shown in figure 3.
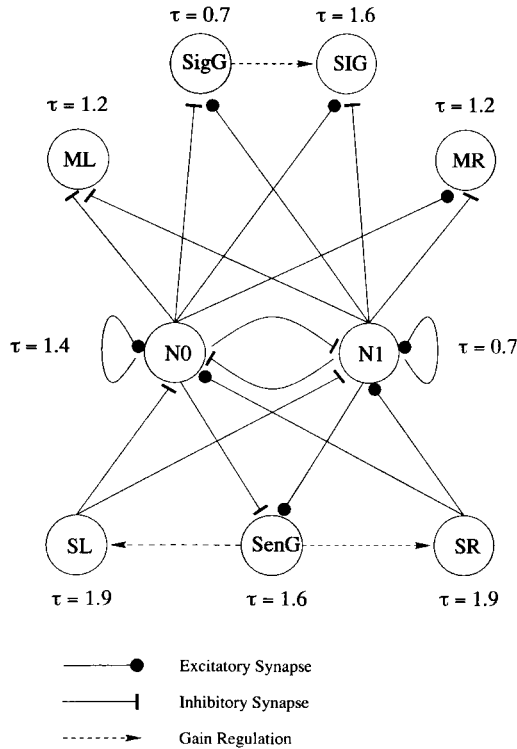

Figure 5. Neuronal structure. N0 and N1: active inter-neurons, MR and ML: motors right and left, SR and SL: sensors right and left, SenG: sensory gain regulation, SIG amplitude of emitted sound, SigG: regulation for sound effector.

self-stimulation is also integrated into the production of movement, as is evident from the fact that if we reduce progressively the capacity to hear their own production, the behavior of the agents degenerates very rapidly into a rotation on the spot. Perturbation can be done by altering the degree of self-stimulation in absolute terms (multiplying the perceived intensity by a factor between 0 and 1) or by introducing delays between the agent's own sound production and perception. We can conclude that the agents are not merely acting on external cues as was suggested in the previous paragraph, but the ability to hear themselves is also integrated into the rest of the behavior. From another point of view, this is also evidence that a functional characterization of signalling behavior as purely conveying information of position, or even of changes of position, is not possible, nor is it possible to decompose movement into active sensing and approaching.

Figure 6 shows the signal produced and the regulated value of the sensory gain for an agent on its own. Figure 7 shows the same for an agent in interaction with another agent. Figures 8 and 9 show respectively the corresponding power spectra[13]. As would be expected from the fact that sensors can 'burn up' due to intense activation, when the agent is emitting an intense signal sensory gain is reduced. We also observe that signalling behavior has a marked rhythm when agents are interacting. What is the origin of this rhythm? It cannot rely entirely upon internal mechanisms since it does not appear when the agent is by itself (figures 6 and 8), although the corresponding
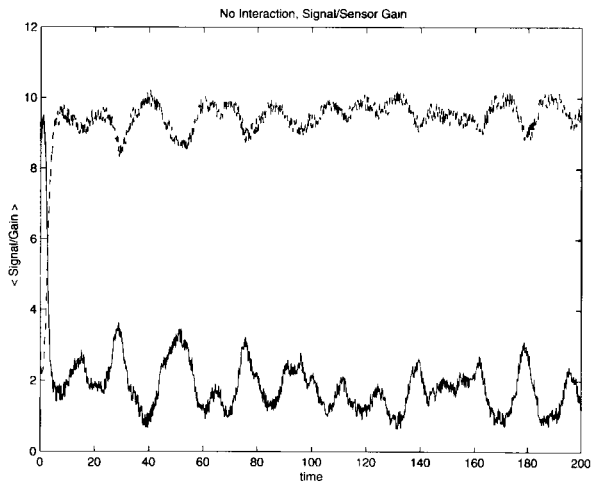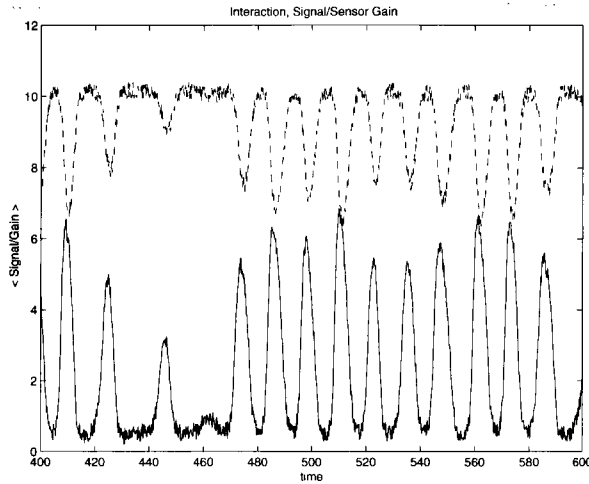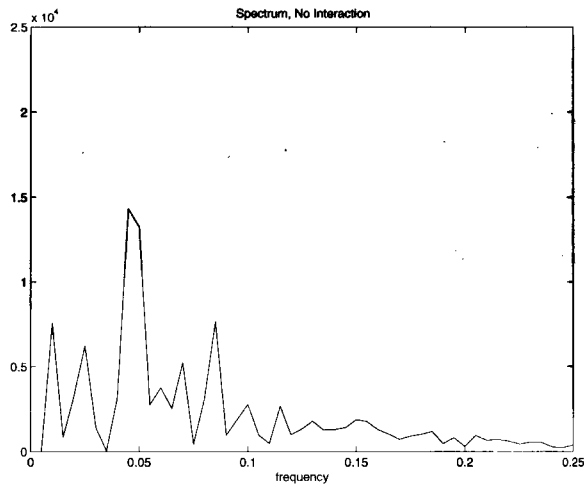

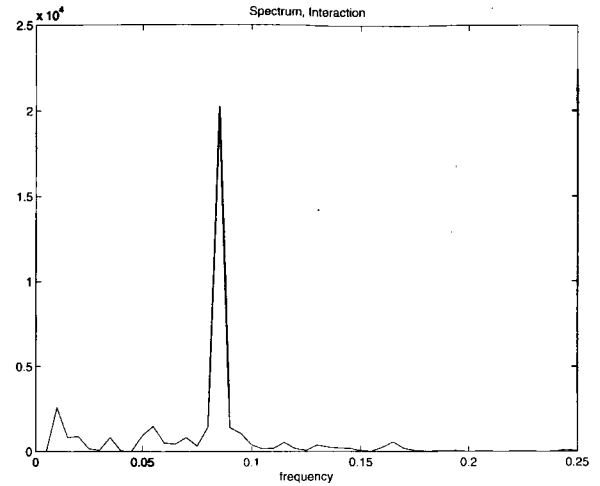**Figure 6. Emitted signal (full line) and sensory gain (dashed line) for an agent by itself.**

Figure 7. Emitted signal (full line) and sensory gain (dashed line) for an agent that is interacting.

Figure 9. Power spectrum for emitted signal of an agent that is interacting.

Figure 8. Power spectrum for emitted signal of an agent by itself.

power spectrum indicates the presence of other frequencies.

From the analysis of frequency spectra, we conclude that rhythm in signalling behavior is directly linked to angular behavior. We reach this conclusion by comparing for one of the agents the frequency of its signal with the frequency of the variation in angular orientation relative to the line connecting both agents, and, finally with the frequency obtained from

the difference of sound intensity at the position of the sensors, (figure 10)[14]. All three spectra show a sharp peak for the same value of frequency.

Additional evidence of a connection between signalling and angular movement is obtained from the observation that, if a source of sound is placed at a fixed distance and angular position with respect to a moving agent (i.e., movement has no influence on
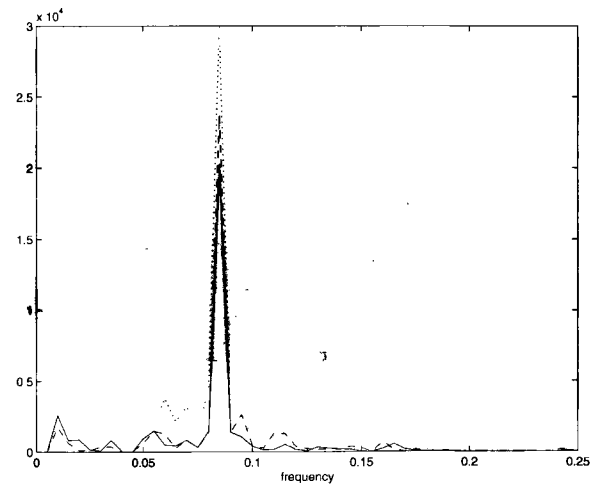
Figure 10. Power spectra for signal (solid line), agent orientation relative to the other agent's position (dotted line) and difference of intensity at sensor position (dashed line).
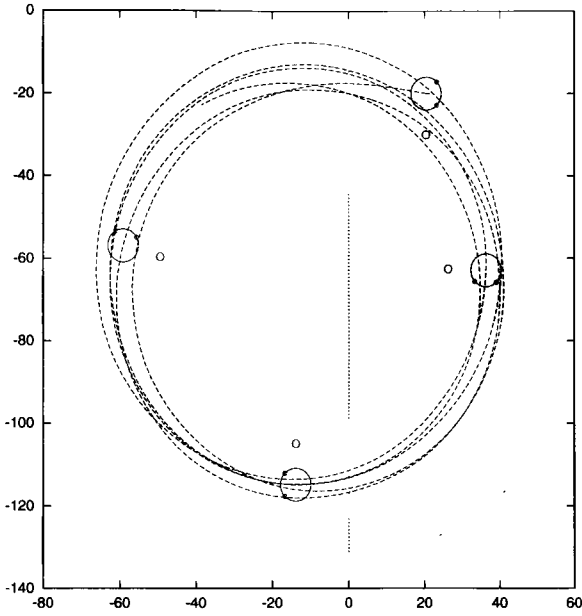
Figure 11. Trajectory for an agent with a constant source placed at a fixed position relative to the agent. The source is represented by a small circle.
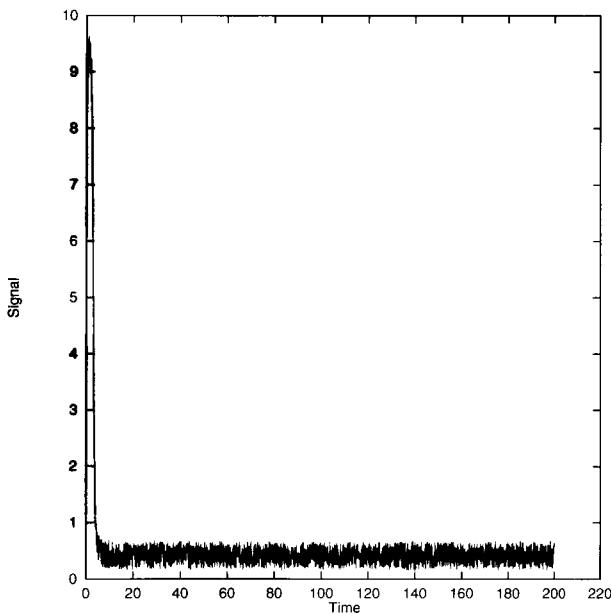
Figure 12. Signal emitted by the agent for constant source. Run corresponds to figure 11.

sensed intensities), all rhythm in signalling behavior disappears. This is shown in figures 11 and 12.

The previous evidence seems to suggest that rhythmic signals originate entirely as a consequence of the angular movement of the agents. However, we must be cautious with this conclusion since, as we said above, movement is not independent of signal production. From the observations made, it could as well be argued that angular movement depends on rhythmic signalling and that rhythm in signals originates somehow within the dynamics of interaction. The first explanation seems more plausible but we have not been able to rule out the second one so far. This difficulty in itself points to the fact that behavior is quite integrated and makes functional decomposition difficult. It gets harder if we consider the global picture of both agents in interaction as will be shown next.

7.2 Entrainment, Turn-taking and Structural Congruence

Since patterns of joint activity are relevant for understanding the behavior of individual agents we now turn to the analysis of these patterns in cases of prolonged interactions. Figure 13 shows the signalling behavior of two interacting agents after having approached one another. Figure 14 shows the corresponding power spectra. We observe that, for long periods, signals are phase-locked at some value near perfect anti-phase. Although agents are similar, they are not identical, and their 'natural' power spectra (i.e., when acting on their own) are indeed different. This suggests that the observed entrainment must somehow be related to the coupling between the agents. Figure 13 (see also figure 19) shows that this entrainment can be lost momentarily only to be regained later. This phenomenon is similar to what we have called relative coordination: the tendency to actively correct for phase-randomizing factors such as fluctuations or differences in natural behaviors or physical properties.

The anti-phase locking of signals can be interpreted as a basic form of turn-taking. Since agents have no other way of knowing of the presence of the other but through acoustic coupling an efficient way of doing this is by alternating the production of signals and so
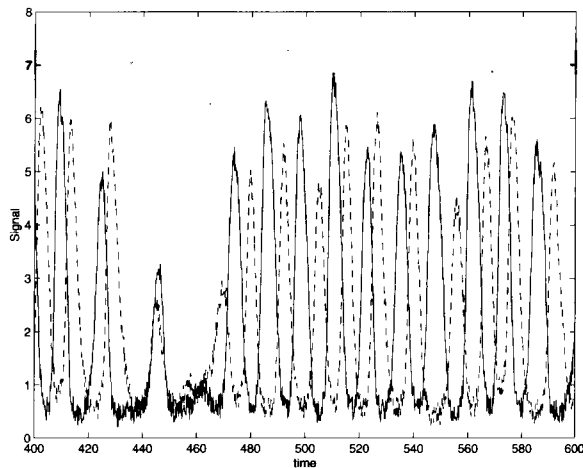
Figure 13. Signalling behavior of interacting agents (a solid line is used for one agent and a dashed line for the other).

Figure 15. Motion of agents during period of coordination. Agents are shown at two time steps. Collisions occur at the bottom sections of the cycloidal trajectory.
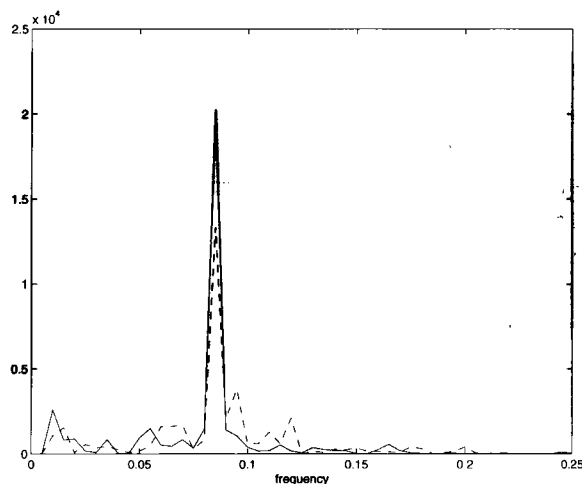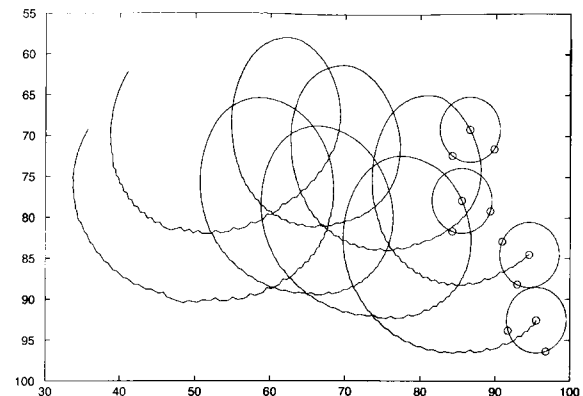

Figure 14. Power spectra for signalling behavior, (a solid line is used for one agent and a dashed line for the other).

minimizing overlap.

Movement during periods of coordination is also highly organized (figure 15). Agents perform almost perfectly synchronized 'dancing' patterns alternating their positions on the inside and outside of a curved trajectory while varying their angle of orientation in an almost identical manner. Agents collide slightly with each other on certain occasions, and this also seems to be an ordered phenomenon (compare the smooth portions of trajectory on the top of figure 15

where the agents are not in contact with the portions at the bottom, collisions occur only in the latter).

We propose that the highly ordered patterns shown by agents both in their movement and signalling behavior are evidence of the achievement of dynamic structural congruence through acoustic coupling. Coordination is achieved jointly by the agents once they have undergone specific, mutually perturbed, transients in their respective dynamics. As much as coordination cannot be reduced to the behavior of a single agent, the specific ordered patterns we observe during coordination cannot be explained by the activity of individual agents if they are indeed the consequence of the structural congruence attained between them. In principle this may seem strange, after all coordination could be conceived as the individual adaptation to the behavior of one's partner instead of a co-adaptation.

In order to prove that coordination in these agents does not originate from an *individual* capacity for adapting we will examine how agents behave in the presence of beacons that produce sound signals. We place a beacon in the arena in a fixed position, and one agent at a random angle, orientation and distance from it. Beacons can produce a variety of signals. In all cases agents approach the beacon successfully but their signalling behavior differs from the case of two interacting agents. Figure 16 shows this signalling behavior when the beacon produces a periodic signal with a period chosen to be equal to the one shown by

coordinating agents. If the agent had an individual capacity to adapt its signalling behavior to the sound perceived we would expect it to show a similar signalling behavior in the presence of the beacon. It does not happen. It can be argued that the frequency used by the beacon is not exactly right. A long simulation in which we perform a slow 'frequency sweep' in the beacon's signal for the whole range of frequencies of interest shows no difference in the signalling behavior of the agent. The possibility still remains that the particular distribution of frequencies may matter. In order to test this we perform the following experiment. A normal simulation with agents in interaction was run, and the signalling behavior of one of the agents during coordination was saved. The 'taped' signal was broadcast from the beacon to the other agent now by itself. The result (see figure 17) shows that phase locking does not occur and signals are not even rhythmic.
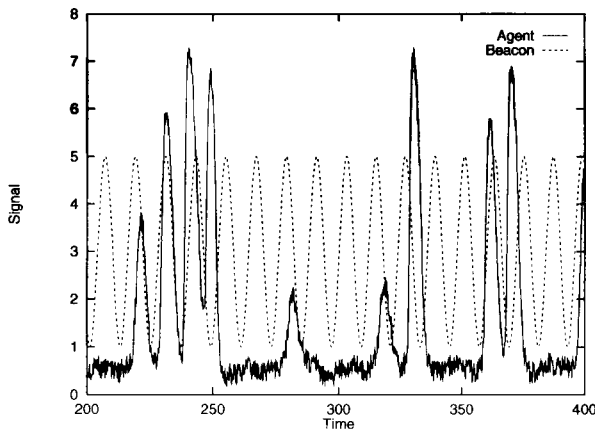

Figure 17. Signalling behavior in presence of imitative beacon.

Figure 16. Signalling behavior in presence of periodic beacon.

All this evidence shows how relevant is the presence of a period of mutual induction of changes in the dynamics of each agent. Beacons are completely non-plastic, and therefore their 'behavior' cannot be influenced by the approaching agent. The lack of a transient period of mutual triggering of changes of state results in no structural congruence, and consequently in no entrainment.

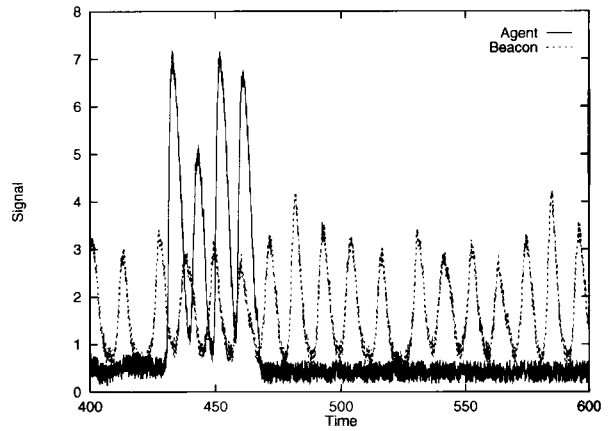So far we have looked only at external manifestations of structural congruence. Figure 18 presents further evidence, this time from internal dynamics. In this figure we observe the embedded time-delayed plots for the activation of the same inter-neuron in two agents under different circumstances. The two plots at the bottom correspond to the agents acting on their own, i.e., no coupling. Here we observe again that although their structures are similar (both neural networks present the same architecture shown in figure 5), they are not identical (parameter values differ slightly) and, consequently, their dynamics have different attractors. The top four plots show the same variable for the interacting agents. The two plots at the top are taken from a period of coordination. We can appreciate the striking similarity between the two attractors as well as the difference between them and the natural dynamics. The plots at the center of the figure correspond to agents interacting but during a period when coordination has been lost. These plots also show an interesting qualitative difference with respect to the other cases. Agents do not return to their 'natural' dynamics when coordination is lost but to a different, uncoordinated state from which it is possible for coordination to be regained, and which suggests that the structure of each agent has changed as a consequence of interaction.
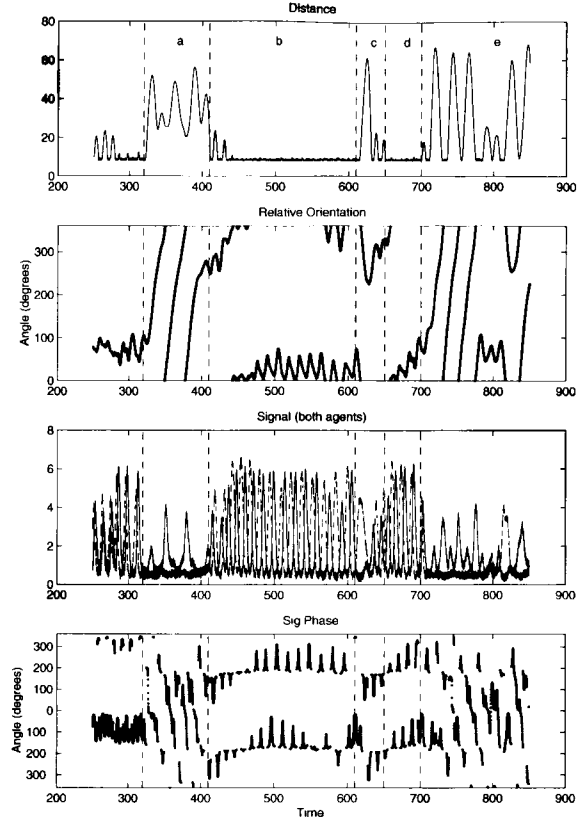
In each case we can calculate the time correlation

$$\rho = \frac{C_{ov}(\mathbf{N}_{A1},\mathbf{N}_{A2})}{S(\mathbf{N}_{A1})S(\mathbf{N}_{A2})},$$
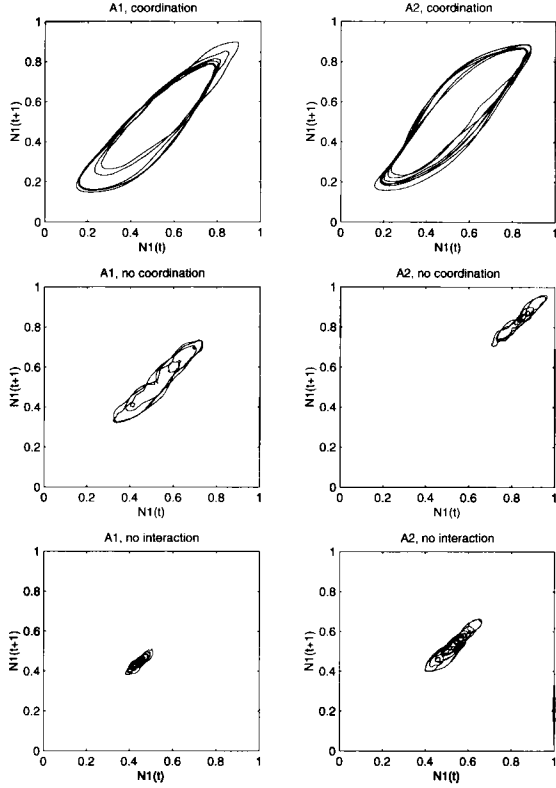
Figure 18. Time-delayed attractor dynamics in the same inter-neuron for two agents (A1 and A2) in different situations. The selected inter-neuron was chosen for clarity in the plots.

Figure 19. Achievement, loss and regaining of coordination. Distance, relative orientation, signals, and estimation of relative signal phase as functions of time.

in neuron activation between the agents:

where $C_{ov}(\mathbf{x}, \mathbf{y})$ is the covariance between variables $\mathbf{x}$ and $\mathbf{y}$, $S(\mathbf{x})$ the standard deviation of $\mathbf{x}$ and $\mathbf{N}_{Ai}$ is the vector composed by the time series of activation values for the inter-neuron in agent i in the period of interest. In the case of coordination $\rho = -0.8443$, for the case of interaction but no coordination $\rho = -0.3750$, and for the non-interacting agents[15] $\rho = -0.0403$. A strong anti-correlation between coordinating agents is in accordance with their signalling behavior.

The transition from a coordinated toward an un-coordinated state can be induced both by fluctuations (noise) or by an instability due to internal differences in the respective dynamics. However, the transition from an un-coordinated state into coordination can only be understood in the presence of an organizing coupling between the two systems since fluctuations

will tend, on average, towards the loss of entrainment. In figure 19 we can see how these transitions occur and how different variables are affected. The four plots are taken from a simulation run with the agents interacting. The plot at the top shows the distance between the agents. Coordination periods are conspicuous since they present a much smaller range of variation in distance. During these periods agents perform the ordered patterns of movement shown in figure 15. These regions are marked "b" and "d". In contrast, periods of no coordination (regions "a", "c" and "e") show greater variation in distance. The second plot shows the relative angular orientation between the agents which remains near zero degrees during coordination and is uncorrelated the rest of the time. The third plot shows signalling behavior, and the plot at the bottom shows a continuous estimation of the relative phase between signals, (the horizontal lines

mark 180 and -180 degrees)[16]. During coordination and even a bit before (compare the beginning of region "d" in the top two plots with the same area in the other plots), signals are produced near the antiphase region. The fact that this correlation is manifested before the attainment of minimum distance suggests that signal coordination may come first, and coordination of movement may be its consequence. This makes sense if we think that signals can begin to be coordinated from a certain distance greater than the minimum.

8 DISCUSSION

Our basic model shows some interesting phenomena like turn-taking and organized movement arising from basic features of the physical nature of acoustic coupling between embodied agents. In interpreting how these phenomena arise we have made use of theoretical concepts concerning social behavior under a systemic, non-functional perspective as well as other concepts taken from the dynamics of coupled oscillators. We think that much is to be gained from this perspective and that we have barely started to explore its potential.

In our model agents interact acoustically, and through this interaction they mutually coordinate their patterns of movement, and they structure their acoustic coupling into a form of alternated production that resembles turn-taking. It is not inconceivable that this result could have been different, (for instance, fairly constant signalling behavior, totally decoupled from movement and perception). Initially we may be surprised that agents organize their interactions in the way they do but we have seen that there is nothing magical about this organization if we analyze the process operationally.

However, providing a thorough operational explanation can be hard. Apart from the potential complexity of such an account, one of the main difficulties lies in the fact that many operational aspects of the system act concurrently, so it is not always possible to speak in terms of causality, as we noticed implicitly in the discussion on the origin of rhythm in signal patterns. Nevertheless, we can formulate a tentative operational route to understanding what goes on in our model. We start from the physical aspects of sound production and perception as operational

assumptions. Embodied agents actively exploit self-shadowing as a localization mechanism by favoring cycloidal movement as a search strategy. Angular movement introduces rhythm in perception which is also manifested in signalling behavior. Rhythmic acoustic signallers become entrained through mutual perturbation for the same reasons other coupled oscillators do under a variety of circumstances, even in the presence of fluctuations and individual differences. Finally, coherent signalling behavior drives patterns of movement into an ordered state.

If the best we can do is to give an incomplete operational account of what happens in an artificial world one may justifialbly ask what is the scientific value of our methodology. Although, as discussed in section 5, our model says nothing about the evolutionary aspects of social coordination, we can consider some implications of our analysis as to how certain evolutionary questions could be framed.

The study of social behavior and its relevance to the evolution and development of human capabilities has often been approached from a purely functional angle. We repeat that there is nothing wrong with this but that functional considerations should be grounded on what we know about the operation (at different levels) of the systems concerned. A functional explanation can be derived from the abbreviation of certain nomic relationships. But without a sufficient exploration of what those relationships might be, we run the risk of missing alternative ways of building functional links as well as the risk of building functional links that disregard operational constraints. For instance, the received wisdom has been in recent years that social life is important for understanding the evolution of human intelligence because social life can be very complex, and our ancestors needed to be good predictors of the outcomes of social interactions[17]. In this theory there is a separation of social life and individual capabilities, and a functional bridge is built between them. This distinction can serve its purpose, as long as it does not become reified into the operation of the various systems involved. Because, at the operational level, even in our simple model the artificiality of this separation becomes evident. In particular, we have found that the use of the same channel for self-stimulation and social interaction makes it difficult to decompose the behaviors of an agent into social and non-social categories. This shows that there

can be direct operational links between what we see as purely social and what we see as purely individual.

A related aspect that shows how the divide between social and individual capabilities tends to permeate into unnecessary operational requirements is the re-discovered fact that behaviors arising from co-adaptation do not necessarily imply an individual capability for performing similar tasks. We saw this in our model when we demonstrated that agents are incapable of entering into coherent signalling behavior with beacons that produce 'artificial' signals, but they can do it with other agents. The successful performance of certain behaviors need not be within the realm of competence of the individual organism if these tasks are performed socially in a coordinated fashion, a fact that should serve as a warning whenever we try to extrapolate operational features (how an organism should work) from functional interpretations of observed evidence (what it does)[18].

To show the potential of our methodology we will finish with a brief comment about how our model could be improved and what else could be studied with it. In section 2 we briefly touched upon some ideas about how social forms of learning could be understood from a systemic perspective as a form of directed structural change due to the achievement of structural congruence between unevenly plastic organisms. The feasibility of this hypothesis could be easily tested by extending our model to include richer forms of plastic change, some of which become gradually 'solidified' during the lifetime of an agent. Some cases of imitative learning could possibly be explained in these terms. But the idea is more powerful still, as it could also explain other phenomena such as the bonding observed between duetting pairs in *Laniarius*. Once some of the structural changes undergone because of mutual perturbation have become 'frozen' in ways that favor following encounters with the same individual(s), social affinity is the unsurprising outcome.

NOTES

[1]An interesting line of research dealing with acoustic interactions using robots is the modelling of the behavior of female crickets in the presence of songs produced by males, (see for instance Lund, Webb, & Hallam, 1997). So far this work has only been focused on reproducing the behavior of females in responding to songs (produced by *real* crickets), so that self-stimulation did not constitute a problem.

[2]Consider the nervous system as a candidate operationally closed system. If we want a dog to perform a trick, and we imagine that this can be achieved by inserting electric currents in specific locations of its brain, in that case the dog's nervous system will cease to act as operationally closed.

[3]The word "structural" originates in a distinction between a system's organization and its physical composite realization or structure (if we are dealing with a physical system). This is how we will use the term in this paper; in particular, when speaking of an organism's or an agent's structure we will be referring to the set of components that constitute the whole of its body including nervous system or controller. At each moment, the state of the system is completely determined by a previous state and by its structure. As physical systems, interactions between two autonomous entities occur between their structures and not their organizations. However, the term would not be as clearly defined if we were dealing with non-physical systems that we presume autonomous (say, a financial market).

[4]Sometimes also called "orientation". However, we will reserve this term to refer in our model to the angular orientation of the agents.

[5]More specific mechanisms, such as the auditory apparatus of the cricket, combine frequency discrimination with enhancement of intensity difference by means of a particular set of delays and filters, (Lund et al., 1997, and literature cited therein).

[6]In humans such coordination is apparent. There is much evidence of coordination between speech and body movements of both speaker and listener, both in adults and infants (Condon & Sander, 1974; Condon, 1979; port, Tajima, & Cummins, 1998). However, a different example may help to put certain distance from specific human behavior and avoid issues that, at this stage, we are not ready to address using the present methodology.

[7]Duetting has also been observed in many monogamous primate species. See (Haimoff, 1986) for a description of the evolutionary convergence of many aspects of duetting in primates of different taxa.

[8]An exploration of the influence of each of the many parameters of our model is not our aim. We will concentrate on analyzing some instances of viable behaviors under the constraints we impose. The significance for natural cases will be given by the validity of the choices we make.

[9]In the simulations reported here we have not used touch sensors that activate when the agents collide. The main reason for this is that we want to explore long-term behavior, even after the agents have successfully approached one another. We have observed in simulations that the introduction of touch sensors can have as a consequence the termination of (translational) movement in the agents after the first collision (i.e., agents find each other, collide and then rotate on the spot in nearby positions).

[10]It must be remembered that after a few generations a large proportion of the population would have converged to similar structures.

[11]This number is determined by the choice of other parameters, such as motor gain and initial distance of separation, in order to make the approaching task possible.

[12]See (Press, Teukolsky, Vetterling, & Flannery, 1992) for a description of these methods.

[13]All power spectra in these and the following figures are calculated by first normalizing the signal to a value between 0 and 1, then subtracting its mean value and calculating the square of the absolute value of the Fast Fourier Transform.

[14]Since the signal produced by the agent reaches its own sensors symmetrically, performing this difference in the value of intensity will also provide information about the angular movement of the agent relative to the external source.

[15]This last value is only illustrative of the different 'natural' behavior of the agents.

[16]This estimation is obtained by a continuous normalization of the signal and its derivative to the unit circle after filtering out the noise, and then calculating the phase difference as a function of time. This is shown in the range between -360 and 360 degrees to aid visualiztion, i.e., the horizontal lines indicate a same phase value.

[17]The so-called Machiavellian intelligence hypothesis, see (Humphrey, 1976), and the collections (Byrne & Whiten, 1988; Whitten & Byrne, 1997).

[18]A simple relevant example is provided in (Di Paolo, 1997) where *state-less* machines in coordination can produce specific *sequences* in the presence of a constant environmental stimulus.

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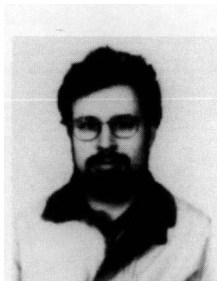
Ezequiel Di Paolo has studied Physics at the Universidad de Buenos Aires, and Nuclear Engineering at the Instituto Balseiro (CNEA-Cuyo) where he received his MSc in 1994. From 1995 to 1998 he did his doctorate on the evolution and development of social behavior under the supervision of Phil Husbands at the School of Cognitive and Computing Sciences, University of Sussex, where he is now working as a lecturer in Evolutionary and Adaptive Systems. His current interests include modelling adaptation to bodily disruptions such as inversion of the visual field, evolutionary models on the persistence of ecological patterns, and methodological aspects of individual-based computational modelling.