Effect of time delays on agents' interaction dynamics

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ABSTRACT

While speaking about social interaction, psychology claims as crucial the temporal correlations between interactants' behaviours: to give to their partners a feeling of natural interaction, interactants, be human, robotic or virtual, must be able to react on appropriate time. Recent approaches consider autonomous agents as dynamical systems and the interaction as a coupling between these systems. These approaches solve the issue of time handling and enable to modelise synchronisation and turn-taking as phenomenon emerging with the coupling. But when complex computations are added to their architecture, such as processing of video and audio signals, delays appear within the interaction loop and disrupt this coupling. We modelise here a dyad of agents where processing delays are controlled. These agents, driven by oscillators, synchronise and take turns when there is no delay. We describe the methodology enabling to evaluate the synchrony and turn-taking emergence. We test oscillators coupling properties when there is no delay: coupling occurs if coupling strenght is inferior to the parameter controlling oscillators natural period and if the ratio between oscillators periods is inferior to $1/2$. We quantify the maximal delays between agents which do not disrupt the interaction: the maximal delay tolerated by agents is proportional to the natural period of the coupled system and to the strenght of the coupling. These results are put in perspective with the different time constraints of human-human and human-agent interactions.

Categories and Subject Descriptors

H.1.2 [**Models and Principles**]: User/Machine Systems
; I.6.4 [**Simulation and modeling**]: Model Validation and Analysis

General Terms

Theory Measurement

Keywords

Human-robot/agent interaction, Multi-user/multi-virtual-agent interaction, Peer to peer coordination,Emergent behavior,Modeling the dynamics of MAS, Agent commitments

1. INTRODUCTION

Cite as: Effect of time delays on agents' interaction dynamics, Ken Prepin and Catherine Pelachaud, *Proc. of 10th Int. Conf. on Autonomous Agents and Multiagent Systems (AAMAS 2011)*, Yolum, Tumer, Stone and Sonenberg (eds.), May, 2–6, 2011, Taipei, Taiwan, pp. XXX–XXX.

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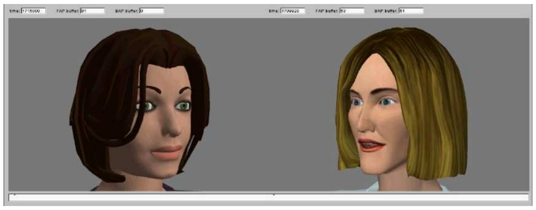
Since 1966, when Condon and Ogston's annotations of interactions have suggested that there are temporal correlations between the behaviours of two persons engaged in a discussion [8, 7], time relations between interactants' behaviours have been investigated in both behavioral studies and cerebral activity studies [24, 26, 27, 38, 21, 35, 43, 29, 30]. These studies tend to show that when people interact together, their ability to synchronise with each other is tightly linked to the quality of their communication: smooth interaction is possible only when partners are online, not only active but reactive [27], responding to each other in a continuously changing flow. Consistently with these results, in the design of autonomous agents, be robotic or virtual, able to interact with human users or other agents, one of the major issues is the "handling of time" [17]. The agents use verbal and non-verbal means to communicate. They are endowed with perceptive capacities allowing them to detect and interpret what their interactant is saying and how. When all the agents are virtual, interacting in a virtual environment, they can have direct access to information about their partners: there is no need of complex signal processing, and time handling is facilitated (see fig.1(a) for such a setting). By contrast, when agents have to interact through the real environment, just as they would have to do with humans, acoustic and visual analysis software is needed to provide information on behaviours as well as high level information such as emotional and epistemic states: these complex processes take time and introduce delays within the interaction loop. As a consequence, agent-agent interaction (as in fig.1(b)) or agent-human interaction cannot be handled as in human-human interaction. Processing delays influence the interaction capabilities of agents dyad. Our aim is to evaluate this influence.

When we refer to the timing of an interaction between agents, be human, robotic or virtual, "real-time" may account for a wide range of time scales. "Real-time" can be defined as: "Denoting or relating to a data-processing system in which a computer receives constantly changing data,[...] and processes it sufficiently rapidly to be able to control the source of the data" [6]. For instance, talking about "real-time" Embodied Conversational Agents (ECA) implies to give on one hand an estimation of processing, answering and animation speed; and on the other hand an estimation of the speed of the systems, human or virtual, agents interact with. Whithin interactions (and given a certain culture), there is a continuum of time scales which may be focused on, depending on the phenonomenon we are talking about:
- for instance in face to face interactions, gaze crossing and synchronous imitations rely on unperceptible delays (< 40*msec*) [9];
- concerning human-human turn-taking, over 70% of between-speaker silences are less than 500*msec* [44], i.e. the approximate simple vocal reaction time to variably-timed cues ([20] cited by [44]);



(a)

(b)

Figure 1: Two agents setup. (a) The two agents are on the same computer, exchange of information between them is fast and coupling occurs (synchrony and turn-taking). (b) The two agents are on two different computers, information exchanged has to be processed: there are longer delays and the coupling does not occur anymore.

- up to 30% of between-speaker silences are less than 200*msec* long, i.e. the simple vocal reaction time over maximally favorable conditions ([16] cited by [44]);
- behaviours modifications in non-verbal interactions are exhaustively coded with $0,4$*sec* time windows [26];
- in human-agent interactions, after 1 second delay humans hardly detect being imitated by the virtual agent and after 4 seconds they do not detect it at all [3].

These time scales are spread from 10*msec* to 4 seconds but we foresee two main timescales to classify agent design studies: >1*sec* time scales systems and 100*msec* time scales systems.
- the >1*sec* timescale enables virtual agents to handle communication of the type emit/receive/answer, i.e. the telegraphist model of Shannon's theory of communication [41]. For instance, if the interaction is a question/answer scenario with only non-verbal behaviours of mean latency such as posture or attitude imitation, a one second delay will not disrupt the interaction. This timescale allows processing delay to appear within the interaction loop, between perception and reaction of agents; this is the rough estimation of timing of many present virtual agents systems, when they interact with human and have to process both video and audio signals and to compute both verbal and non-verbal behaviours to display.
- the timescale around hundreds of milliseconds comes from psychological studies of interaction. This is the time scale associated to changes of gaze direction, facial expression and accoustic prominence; these behaviours are necessary to give to human users the sense of ECA engagement; a one second delay can completely disrupt this feeling [3]. The model of fast and automatic appraisal, triggers very quick reactions (<100*msec*) [22]. It claims that reactive and very rapid influence of stimuli on behaviour is crucial. This model associates this quick reaction to a larger time scales (nearer the second) which enables top-down modulation of the behaviour.

Recent approaches in psychology [26], neuro-dynamics [9] and agent design [31, 15, 37, 32] proposes that communication is a coupling between dynamical systems and stress the issue of time handling: agents, when coupled together with their interactants, constitute a new, larger and richer, dynamical system. For instance turn-taking and synchrony can be modeled as emerging from the coupling between oscillators [44, 37, 42]. These approaches point to the fact that, during an interaction, participants are continuously active, each modifying its own actions in response to the continuously changing actions of its partners. They highlight the necessity to handle small timescales to build agent capable to interact with humans, and capable to give them a feeling of shared understanding [36].

In our paper, given a specific time scale, we study the range of delays in the interaction loop which do not disrupt the interaction. In particular we study the effect of time delay on coupling between two agents. We simulate simulate them by two oscillators using a model similar to [37].

In the remaining of the paper, we first remind the psychological and neurological background on interaction and coupling, as well as their existing robotics and virtual implementations as oscillatory systems. In Section 3 we describe our model of dyad of oscillators. Then, in Section 4, we test the coupling properties of such a dyad, i.e. we analyse the emergence of coupling depending on the difference between natural periods of oscillators and reciprocal influence between oscillators. In Section 5, we test if delay in the interaction loop has a crucial effect on the coupling capability of the dyad. Finally, in Section 6, we discuss these results and their outcomes.

2. DYNAMICAL APPROACH OF INTERACTION

The dynamical approach of interactions is sustained by psychological studies which tend to show that dyadic parameters of interaction (such as synchrony) are phenoma emerging from the coupling occurring between interactants. In mother-infant interactions via the "double-video" design (which enables a teleprompted interaction to be modified online by experimenters), synchrony is shown to emerge from the mutual engagement of mother and infant in interaction [24, 26, 27]. In adult-adult interactions mediated by a technological device which restrains perception to only tactile stimulation, coupling between partners has been shown to emerge from the mutual attempt to interact with the other [2]. Other studies focus on the "Unintentional Interpersonnal Coordination", in both behavioral studies [38, 21] and cerebral activity studies [35, 43, 29, 30]. These studies show that synchrony emerges even when people do not intentionaly interact. Synchrony is shown as emerging from the coupling which takes place between people when cross-perception is enabled (cross-perception occurs when two interactants perceive each other simultaneously: eye contact or touch are cross-perceptions [2]).

These phenomena are echoed by physics and theoretical studies on oscillators coupling. Huygens discovered in 1665 that the pendulums of two clocks hung together synchronise in anti-phase after a while [14]. The model explaining the anti-phase synchronisation of the pendulums has been proposed three hundred years later [23]: when the two pendulums oscillate, they make the support moves. These movements of the support provide little exchanges and loss of energy between the two oscillators. The furthest from anti-phase the pendulums are, the larger the movement is and thus the highest the exchange and loss of energy is. The anti-phase synchronisation is the unique stable attraction basin of this dynamical system. This explains Huygens' observations.

The more general issue of coupling between non-periodic oscillators such as chaotic oscillators has been studied by [39, 40, 13, 18, 4] following the pioneer model of *Synchronization in Chaotic Systems* from Pecora and Carroll [33].

The stability of these coupling states leading to turn-taking (anti-phase) and synchrony (constant phase-shift) is a direct consequence of the reciprocal influence between agents. It has already been implemented for robotics [37] and for virtual agent coupling [32].
- In the robotic experiment, two robots controlled by neural oscillators are coupled together by their mutual influence: turn-taking and synchrony emerge [37].
- In the virtual agent experiment, Evolutionary Robotics[1] was used to design a dyad of agents able to favor cross-perception situation; the obtained result is a dyad of agents with oscillatory behaviours which share a stable state of both cross perception and synchrony [32].

Coupling Model Principles.

These two implementations are quite simple: both signals emitted and received by the agents are one dimension signals and very few computational processes are done on them (by contrast, when visual perception is involved such as in human-agent interaction, images of video are bi-dimensional signals which require complex computational processes). It allows for very fast processing time with time delay negligible compared to interaction timing. It enables an easy coupling with the emergence of both turn-taking and synchrony. We reproduced these experiments with a dyad of 3D humanoid virtual agents. If the two agents are on the same computer and agents have a copy of the other agent's behavior (see fig. 1(a)) the signals are exchanged without any treatment: no time delay is introduced within the interaction loop and coupling occurs. By contrast, if each agent is on its own computer and relies on acoustic and visual analysis to get information on the other as in fig. 1(b) setting, the coupling does not occur anymore. We believe this effect is due to the complex audio-video processing which introduces time delay in the interaction loop between agents.

This last setting is equivalent to human-agent systems when human's motion is analysed and sent to the agent. In our work we are relying on Watson [25] that provides head motion in interactive time. The mean time to get data concerning the partner (e.g type of head movements) is about 1*sec*.

We test this model and its sensitivity to time delays by implementing a dyad of agents as a NN (Neural Network) in the NN Simulator Leto/Prometheus (developped in the ETIS lab. by Gaussier et al. [11, 12]). Leto/Prometheus simulates the dynamics of NNs by an update of the whole network at each time step; it also enables to simulate coupling between agents comparable to coupling through the real world [37]. These two oscillators control the behaviours of two virtual agent implemented with the system Greta [**?**]. This system enables one to generate multi-modal (verbal and non-verbal) behaviours with accurate timing.

3. OSCILLATOR COUPLING MODEL

In both robotic and virtual agent modelisation of turn-taking, two properties must be satisfied by every agent [37]: each agent has to alternate between an active state and a receptive state; these states have to be influenced by the actions of the other agent. When agents having these two properties are placed in the same environment, turn-taking emerges [37].

[1] Evolutionary Robotic is a "technique for automatic creation of autonomous robots [...] inspired by the Darwinian principle of selective reproduction of the fittest" [28] preface

To satisfy these conditions, agents are controlled by two states oscillators: one state orientates the agent to be active (the agent initiates actions in imitation games, and speaks in dialogues); the other state orientates the agent to be receptive (the agent imitates in imitation games, and listens in dialogues). This oscillator is influenced by the other agent's behaviour: it is pushed toward receptive state when the other agent is active. These two properties make a dyad of agents have one stable state, phase-opposition (in dialogue systems, they speak alternately).

3.1 The oscillator

The oscillator is made of two neurons (N_i), whose activities are bounded between -1 and 1. N_1 is the state of the agent: in our case, when $N_1 = 1$ the agent speaks, and when $N_1 = -1$ the agent listens. These neurons activate and inhibit each other proportionally to the parameter α. α constrols the natural period of the agent's oscillator, i.e. the speed of oscillation between speaking and listening states. This model fits the set of equation 1 (see also fig.2(a)).

$$\begin{cases} N_1(t+1) = N_1(t) - \alpha \cdot N_2(t) \\ N_2(t+1) = N_2(t) + \alpha \cdot N_1(t) \end{cases} \quad (1)$$

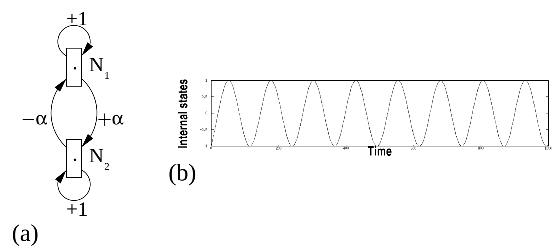


Figure 2: (a) The oscillator is made of two neurons, N_1, and N_2, with a self-connection weighted to 1. A link with weight $+\alpha$ connects N_2 to N_1 , and a link with weight $-\alpha$ connects N_1 to N_2. (b) Activation of this oscillator when it is isolated from any external influence.

We can make the approximation $N_i(t+1) - N_i(t) = N_i'(t)$ if α is small enough, i.e. if $N_1(t)$ and $N_2(t)$ vary almost continuously: with $\alpha < 0.2$ they vary between -1 and $+1$ in more than 10 time steps (see fig.**??** for an illustration of this issue). Making this approximation, the system of equations 1 becomes:

$$\begin{cases} N_1'(t) = -\alpha \cdot N_2(t) \\ N_2'(t) = \alpha \cdot N_1(t) \end{cases} \quad (2)$$

By deriving these equations, we obtain the following set of differential equations:

$$\begin{cases} N_1''(t) = -\alpha^2 \cdot N_1(t) \\ N_2''(t) = -\alpha^2 \cdot N_2(t) \end{cases} \quad (3)$$

Finally the general solutions of such equations, $N''(t) + \alpha^2 \cdot N(t)$, are the oscillatory functions of equation 4:

$$N(t) = Asin(\alpha t + \phi) \quad (4)$$

where A is the constant oscillator amplitude and ϕ its phase: in our case, when the oscillator is isolated, it starts with a null activation, $A = 1$ and $\phi = 0$. The implementation of this oscillator in the Leto/Prometheus simulator makes the neuron N_1 produces the sinusoidal signal plotted on fig.2(b).

3.2 The coupling

Let us consider a dyad of oscillators N and M. To enable mutual influence between them, the main neuron (N_1 and M_1) of each oscillator should directly (weakly) inhibit the main neuron of the other, see fig. 3. The *inhib* parameter controls the sensitivity of the agent to the other agent's speaking turn: if *inhib* is low, speech overlapping is tolerated by the agent, whereas if *inhib* is high the agent will be quiet as soon as the other agent speaks.

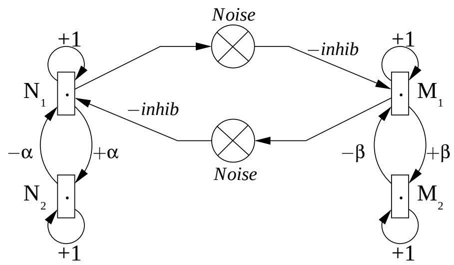


Figure 3: Architecture of the two agents influencing each other. Each agent is driven by an internal oscillator and influences the other depending on this oscillator. When real effectors (such as robotic arms) or/and captors (such as camera) are used, noise is added to signal by the environment. In simulation this noise has to be simulated to enable the agent to anti-synchronize and avoid oscillation death.

For the oscillators, N and M, the set of equations 2 becomes:

$$\begin{cases} N_1'(t) = -\alpha \cdot N_2(t) - inhib \cdot M_1(t-1) \\ N_2'(t) = \alpha \cdot N_1(t) \end{cases} \tag{5}$$

and

$$\begin{cases} M_1'(t) = -\alpha \cdot M_2(t) - inhib \cdot N_1(t-1) \\ M_2'(t) = \alpha \cdot M_1(t) \end{cases} \tag{6}$$

Fig. 4 shows an example of coupling when the oscillators inhibate each other: the two oscillators start in phase, $N_1(t_0) = N_2(t_0) = -1$, and after a period of mutual perturbation, they stabilise in anti-phase. It is important to note here that, in simulation, noise must be added to the signals exchanged between agents [37]: it is to be contrasted with real situations where noise is naturally present in the environment, effectors and captors; in simulation, if oscillators have the exact same period and phase, and if there is no noise, they stay in the unstable in-phase state and inhibit each other until death.

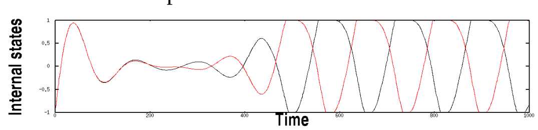


Figure 4: Activation evolution over time of each oscillator of the two systems, for $\alpha = \beta = 0.05$, $-inhib = -0.01$. The two systems start in the same state: at time $t = 0$ the activation of their oscillator is 0. When the oscillators start to activate, they inhibit each other and one takes the advantage. After a transition period, the oscillators are stabilised in phase opposition.

The dynamics of the dyad of oscillators is different from the simple sum of each oscillator dynamic. Even in the fig. 4 where the two oscillators have the same natural period, the period observed after coupling differs from this natural period: natural periods is around 125 time steps for both oscillators whereas, the Dyad's Natural Period (DNP) once coupled is around 160 time steps. It depends on both the natural periods of oscillators, α and β, and on their reciprocal inhibition *inhib* (see Section 4.2).

4. COUPLING ANALYSIS

Each dyad of agents is characterised by a set of three parameters: α, the speaking/listening period of agentN, β the speaking/listening period of agentM, and *inhib*, the reciprocal influence between these agents. Coupling occurs between agents if they manage to reach a shared stable state, even when α and β are different. Here coupling occurs if agents speak alternately, i.e. if their internal oscillators synchronise in anti-phase.

4.1 Evaluation methodology

For a given set of parameters (α, β, *inhib*), to determine if anti-phase synchronisation occurs between agents, we use a procedure described by Pikovsky, Rosenblum and Kurths in their reference book "Synchronisation" [34]. This procedure consists in comparing the phases of two signals to determine if they are synchronous or not.

Let us recall that "the phase of narrow-band signal such as the one produced by our oscillators (sinusoid) can be obtained by means of the analytic signal concept originally introduced by Gabor [10]" [34]. To implement this, we have to construct the complex process $\zeta(t)$ from the scalar signal $N(t)$:

$$\zeta(t) = N(t) + iN_H(t) = A(t)e^{i\phi(t)} \tag{7}$$

where $N_H(t)$ is the Hilbert transform of $N(t)$ [34].

The instantaneous phase $\phi(t)$ and amplitude $A(t)$ of the signal are thus uniquely determined from equation 7.

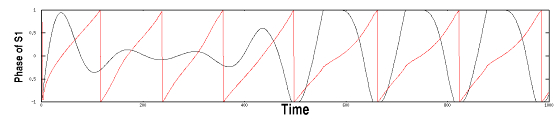
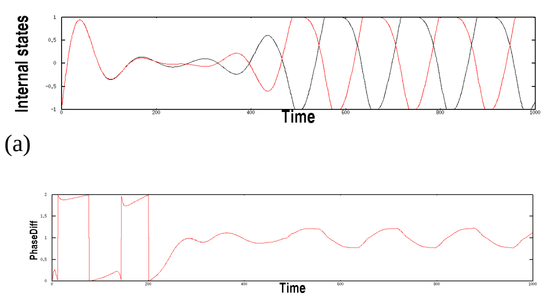


Figure 5: Signal and phase (modulo π), $\alpha = \beta = 0.05$ and $-inhib = -0.01$. The almost sinusoidal signal is the original signal $N_1(t)$ (shown in fig.4) and the almost linear (modulo π) signal is its associated re-built phase.

After that, when the phases $\phi_N(t)$ and $\phi_M(t)$ of the signals are obtained, we consider their difference modulo 2π: if $\phi_N(t) - \phi_M(t)(2\pi) = 0$, signals are in phase; if $\phi_N(t) - \phi_M(t)(2\pi) = \pi$, signals are in anti-phase (see fig.6). Horizontal plateaux in this graph reflect periods of constant phase-shift between signals, i.e. synchronisation. Horizontal plateaux near one $(1 \cdot \pi)$ reflect periods of anti-phase synchronisation.



(a)

(b)

Figure 6: (a) Internal activations of two agents ($\alpha = \beta = 0.05$ and $-inhib = -0.01$). (b) Associated phase-shift $\Delta_{\phi_1,\phi_2}(t)$. When agents synchronise in anti-phase, their phase-shift remains near $1 \cdot \pi$.

For each 5000 time steps simulation, we define that phase-lock occurs if the two following properties are satisfied:

- First, the phase-shift $\Delta\phi_{N_1,M_1}(t)$ becomes almost constant at time $t_{phaseLock}$ (time defined in time steps), smaller than 4000 time steps (1000 time steps before the end of the simulation), and remains constant until the end.
- Second, if $t_{phaseLock}$ exists, the DNP (Dyad's Natural Period) after $t_{phaseLock}$ is finished (we note $T_{finished} = 1$). It is not the case if the inhibition between oscillators is too high (see Section 4.2, fig. 8): $\Delta\phi_{N_1,M_1}(t)$ becomes constant but oscillators do not oscillate anymore; one remains high whereas the other remains low; DNP is infinite (then we note $T_{finished} = -1$).

We defined the locking speed as $PhaseLockSpeed = (4000 - t_{phaseLock})/4000 \times T_{finished}$. If phase-lock is immediat with finished DNP, $PhaseLockSpeed = 1$; if phase-lock occurs at $t =$

4000, *PhaseLockSpeed* $= 0$; and if there is no finished DNP, *PhaseLockSpeed* < 0. For instance, with the previous parameters, $\alpha = \beta = 0.05$ and $inhib = 0.01$, the phase-lock occurs with a speed near 0.8 and for a phase shift equal to π (i.e. anti-phase locking).

These automatic calculs of *PhaseLockSpeed*, *PhaseShift* and *Period* enable us to test the ability of a given dyad of agents (characterised by α,β and *inhib*) to take turns (synchronise in anti-phase).

4.2 Test of Parameters

The parameters usually tested in such a coupling between oscillators are they natural periods ratio α/β and their mutual inhibition $-inhib$ [34]. We briefly test here these properties of the dyad of oscillators.

Reciprocal influence.

For given $\alpha = \beta = 0.05$, we test the influence of reciprocal inhibition on the coupling: if inhibition is too low, no coupling is possible (or after a very long time if the two oscillators have the exact same period), and if inhibition is too high, the two oscillators do not oscillate anymore, one stays high and the other stays low, the dynamic of the dyad is disrupted (see fig.7).

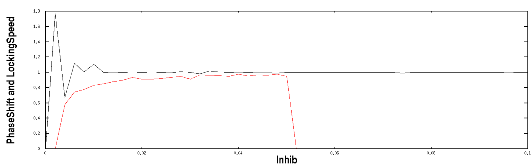
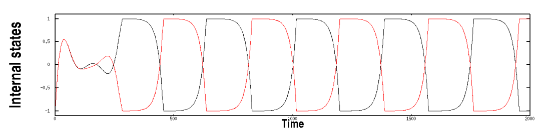
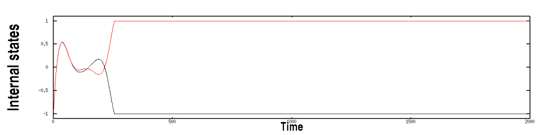


Figure 7: The plain line represents the phase shift when phase-lock occurs (a phase shift equal to 1 is for anti-phase, $\Delta\phi_{N_1,M_1} = \pi$), and the dotted line represents the locking speed. For *inhib* > 0.050, a phase lock equal to π is shown but oscillators do not oscillate, one remains high and the other remains low (see fig. 8).

Coupling occurs when phase-lock occurs, phase-shift is equal to 1π and periods of oscillators are finit. For the oscillator parameters $\alpha = \beta = 0.05$, the highest reciprocal inhibition between oscillators which enables coupling without killing oscillations is $inhib_{limit} = 0.05$ (see fig. 8). Actually, $inhib_{limit} \simeq \alpha, \beta$, i.e. inhibition sould not be higher than the internal weights of oscillators.



(a)



(b)

Figure 8: Activation of the two oscillators for reciprocal inhibition: (a) $inhib = 0.05$ and (b) $inhib = 0.052$. For *inhib* > 0.050, oscillators do not oscillate anymore, one remains high and the other remains low.

Ratio between natural periods of oscillators.

Let us test the influence of α/β variation on the coupling. The reciprocal inhibition is fixed to $inhib = 0.05$, the oscillator$N$'s parameter is fixed to $\alpha = 0.05$ and the oscillator$M$'s parameter varies between $\beta = 0$ and $\beta = 0.3$ with a 0.002 step (see Fig.9). **figure***

For reciprocal inhibition $inhib = 0.05$, if α/β differs from 1 too much, oscillators do not lock in anti-phase: when α/β decreases (β increases), the DNP increases until the second oscillator oscillates several times during one oscillation of the first (for $\beta = 1.3$); conversely, when α/β increases (β decreases), DNP decreases until there is not anymore oscillation (for $\beta = 0.03$) (see fig. 9,(a)).

5. TEST OF DELAY EFFECT

In order to test how a delay in the processing of signals affect the ability of an agent to couple with another, we introduce in our dyad of agents a delay in the reciprocal inhibition (see fig.10). This delay will account for exactly what happens when we go from agents interacting altogether in the same virtual environment to agents interacting via the real world with other agents or with humans. Processing of audio and video signal introduces delays between the perception and the availibility of the information within the system.

A null delay means that the signal is immediatly transmitted, a delay d means that the signal transmitted is the signal which occurred d time steps before (see sets of equations 8 and 9). The "delay box", records d signals in a fifo queue.

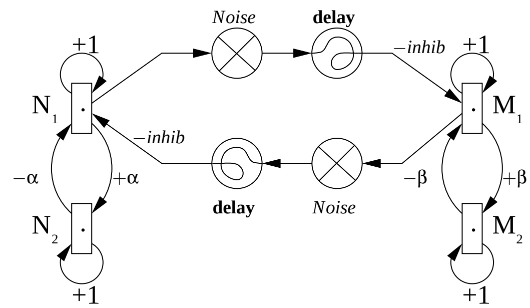


Figure 10: Architecture of the two agents influencing each other. Each agent is driven by an internal oscillator and influences the other depending on this oscillator. The signals exchanged between agents are delayed by d time steps.

With the delay d, the two sets of equations 5 and 6 become:

$$\begin{cases} N_1'(t) = -\alpha \cdot N_2(t) - inhib \cdot M_1(t-1-d) \\ N_2'(t) = \alpha \cdot N_1(t) \end{cases} \quad (8)$$

and

$$\begin{cases} M_1'(t) = -\alpha \cdot M_2(t) - inhib \cdot N_1(t-1-d) \\ M_2'(t) = \alpha \cdot M_1(t) \end{cases} \quad (9)$$

Test of the delay for $\alpha = \beta = 0,05$.

To evaluate the effect of the delay, we test the coupling capability of the dyad for different values of d. We make d vary from 0 to 100 time steps and calculate for each experiment the speed of anti-phase locking between the agents as well as the DNP (see fig.11).

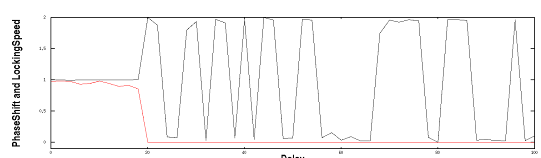


Figure 11: $\alpha = \beta = 0.05$ and the transmission delay d varies between 0 and 100 time steps ($inhib = 0.01$). The plain line represents the phase lock when it occured (a phase lock equal to 1 is for anti-phase, $\Delta\phi_{N_1,M_1} = \pi$), and the dotted line represents the locking speed.

Figure 11 shows that, with $\alpha = \beta = 0.05$ and $inhib = 0.05$, as soon as the delay d is above 18 time steps, the coupling is disrupted: locking speed is null and the phase shift is around $0 (2\pi)$. Agents

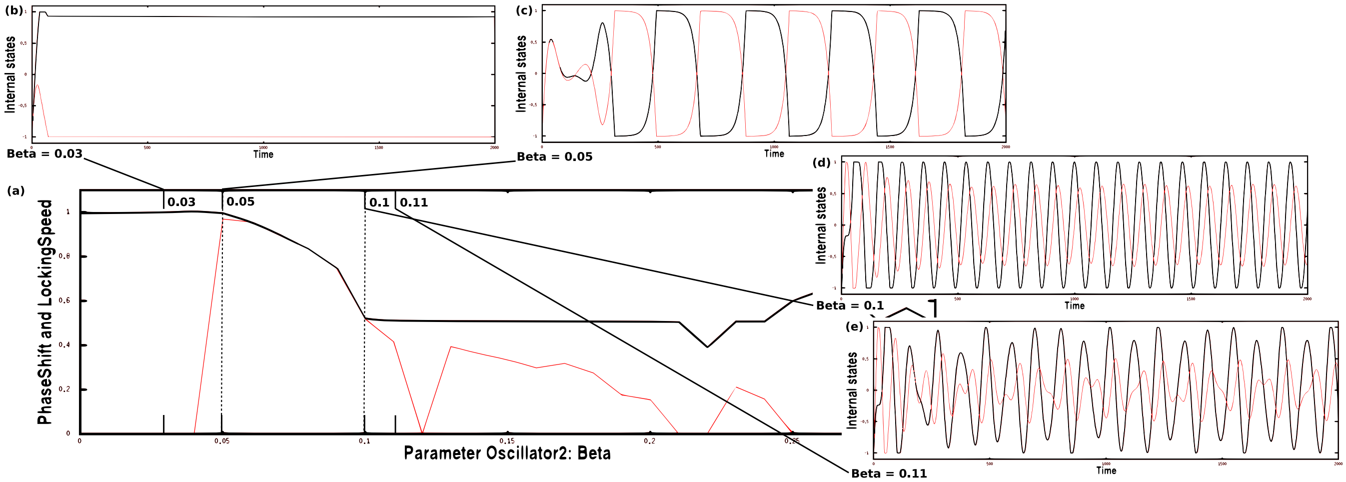


Figure 9: (a) $\alpha = 0.05$ and β varies between 0 and 0.3 (with a 0.002 step). The plain line represents the phase lock when it occurs (a phase lock equal to 1 is for anti-phase, $\Delta\phi_{N_1,M_1} = \pi$), and the dotted line represents the locking speed. For reciprocal inhibition $inhib = 0.05$, if α/β differs from 1 too much, oscillators do not lock in anti-phase anymore: for $0.5 < \alpha/\beta < 1$ there is still a phase lock but with a phase shift varying from π to $\pi/2$; for $\alpha/\beta > 1.25$ ($\beta = 0.04$) the two oscillators stop oscillating. (b)(c)(d)(e) Activation of the two oscillators for the different natural periods of second oscillator: (b) $\beta = 0.03$; (c) $\beta = 0.05$; (d) $\beta = 0.1$, (e) $\beta = 0.11$.

have the same natural period ($\alpha = \beta = 0.05$) and start with the same phase ($\Delta\phi_{ini} = 0$), by consequence their phase shift is naturally near 0 or 2π when no coupling is possible.

To test how this Maximal Tolerated-Delay (MTD) depends on the three parameters of the dyad, we first test if it is proportional DNP.

Test of the delay for $0.00 < \alpha = \beta < 0.30$.

For $inhib = 0.03$ and $0.01 < \alpha = \beta < 0.3$ the DNP of the coupled system obtained are displayed on fig.12.

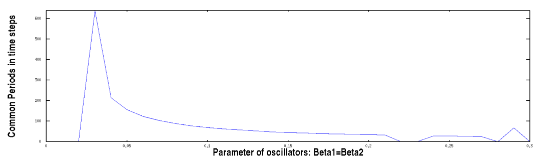


Figure 12: DNP (Dyad's Natural Period). Under $\alpha = \beta = 0.03 = inhib$ no coupling occurs. Above $\alpha = \beta = 0.21$ coupling appears chaotic.

At this point, we can notice two things:
- Under $\alpha = \beta = 0.03 = inhib$ no coupling occurs: α and β are lower than the reciprocal inhibition *inhib*; The internal dynamics of oscillators are disrupted as soon as agents are put together (we observe the same phenomenon for $inhib = 0.05$).
- Above $\alpha = \beta = 0.2$ coupling appears chaotic: $N_1(t)$ and $M_1(t)$ cannot be considered as variing continuously (see Section 3.1); they switch unpredictibly between positive and negative values, constant phase-opposition is not a stable state of the system.

These phenomenons are independent from the study of the delay but they will infuence our results.

In the same conditions ($inhib = 0.03$ and $0.01 < \alpha = \beta < 0.3$) we test the effect of delay, $0 < d < 50$. Figure.13 shows the phase-lock speed obtained for every couple $(\alpha = \beta, d)$.

We can notice here that above a certain delay, the Maximal Tolerated Delay (MTD), coupling is disrupted. But when the delay is a multiple of the DNP, coupling is enabled again.

For $inhib = 0.03$, coupling occurs between $\alpha = \beta = 0.03$ and $\alpha = \beta = 0.2$. Between these values, the curves of the DNP and the MTD are almost proportional: $MTD = 0.15 \times DNP$, with a correlation coefficient equal to 0.99.

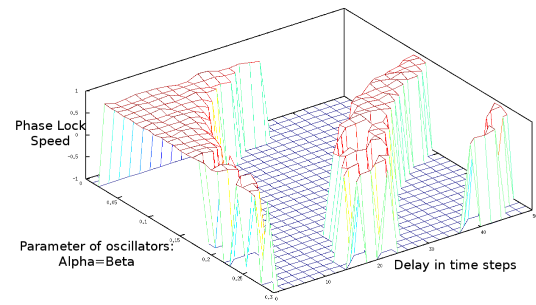


Figure 13: Phase-lock speed obtained for couples $(\alpha = \beta, d)$ with $0.01 < \alpha = \beta < 0.3$ and $inhib = 0.03$. A null phase lock-speed account for no stable coupling, and a phase-lock speed equal to 1 accounts for a quick and robust anti-phase coupling.

Doing the same simulations, extraction of phases, and calculations of phase-locking, for different coupling strengh $inhib = 0.01$ and $inhib = 0.03$, the DNP and MTD also appeared proportional. For $inhib = 0.01$, $MTD = 0.18 \times DNP$ with a correlation coefficient equal to 0.99, and for $inhib = 0.05$, $MTD = 0.12 \times DNP$ with a correlation coefficient equal to 0.97.

The MTD appeared to be proportional to both the DNP and to the coupling strengh: $MTD = (0.195 - 1.5 \times inhib)DNP$ with a correlation coefficient equal to 0.99.

6. DISCUSSION AND CONCLUSION

We have described the implementation of a dyad of agents controlled by oscillators and influencing each other: this dyad enables synchrony and turn-taking to emerge when coupling occurs. We have then described the methodology used to evaluate coupling between these agents and tested the parameters of this dyad: the ratio between the natural periods of agents behaviours; the reciprocal inhibition between agents. Our results show two main facts concerning oscillators modeled by neurons:
- First, that the internal variables of the oscillators (α for AgentN and β for AgentM) fix the maximal external influence the oscillator tolerates without the death of their oscillations.
- Second, given the step by step update of the NN by the NN Simu-

lator, when the weight of the connection is over 0.20, the activation of the neuron does not vary continuously anymore and becomes chaotic.

Considering these results, we tested how a delay in the transmission of signal between agents impacts the capacity of the agents to couple. We tested the set $\{0 < \alpha < 0.3, 0 < \beta < 0.3, inhib \in \{0.01, 0.03, 0.05\}\}$ for $0 < d < 100$.

The first result concerning delay is that it has an effect: a too long delay disrupts coupling. As conjectured in the introduction, when agents interact in the wild world (e.g. Human-Agent interaction, see fig.14), the complex computation of video signals they have to perform introduces delays in agents communication which may disrupt their coupling capabilities.

Figure 14: Experimental design for evaluation Human-Agent interaction. Both human and agent are video-taped for coding.

Second, delays appeared as having an all or none effect: coupling occurred rapidly or did not occur at all.

The third result is that the Maximal Tolerated Delay (MTD, the maximal delay enabling coupling of the dyad), depends proportionally on both the Dyad's Natural-Period (DNP, which depends on α and β) and the coupling strength (i.e. the reciprocal inhibition *inhib*):
- For a given coupling strength, the MTD increases when the DNP increases: If the coupling concerns long period phenomena such as posture imitations, the MTD will be longer than if the coupling involves fast phenomena such as smiles or gaze direction imitations.
- For a given DNP, the MTD increases when the coupling strength decreases: If the DNP is fixed, when the mutual influence between agents decreases, the effect of the delay decreases too (the MTD is higher).

These results do not only concern interactions between agents but they are also relevant for human-agent interactions and human-human interactions. As we have seen in Section2, both psychological and neurofunctional models of human-human interactions [24, 26, 27, 35, 43, 38, 21, 29, 30, 2] claim that dynamical coupling between humans is an essential aspect of their communication: it enables non-verbal interaction but it can also be seen as a complementary part of the verbal exchange [36] which leads to feelings such as rapport and mutual engagement .

Based on the facts just listed, the design of agents dedicated to interact with humans needs to integrate coupling dimension. As we know, time constraints have to be satisfied when we speak about interaction. The present paper gives a rough estimation of the MTD according to the timescales of the considered coupled behaviour. For instance, during dialog between a speaker and a listener, if the mean time between successive backchannels (listener's acknowledgements [45]) is about 3*sec* [1], the signals which may enable to regulate this timescale cannot be delayed more than 18% of this time scale (see Section 5), i.e. the timing of backchannels must be accurate at more or less 500*msec* (i.e. more accurate than the verbal reaction time to unpredictable signal [44]).

Considering these results obtained for agents interacting within the same virtual environment and with an artificial delay, our future work involves two directions:
- A theoretical way. The MTD should be quantified by adding delay in mathematical models, such as the Kuramoto model of coupling between oscillators [19].
- An experimental way. We propose to test the effect of a controlled delay on the coupling between our agent and a human interacting in a cooperative task, for instance the maze task of [5]. This task involves two humans; A character is lost in a maze; One of the subjects sees the maze and the character; the other has the commands to control the character; Both have to cooperate to find a way out the maze. This task induces rhythmic patterns of interaction in which delays can be controlled. By replacing one of the two humans by our virtual agent, the MTD can be estimated regarding the task timescale. The significance of delay can be addressed: the delay can be intentionally added in order to transmit information concerning understanding [36] or in order to disrupt interaction in case of disagreement.

Acknowledgements

This work has been partially financed by the European Project NoE SSPNet (Social Signal Processing Network). Nothing could have been done without the Leto/Prometheus NN simulator, lend by the Philippe Gaussier's team (ETIS lab, Cergy-Pontoise, France).

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