PH.D. PRESENTATION

Analysis of synchronization and leadership emergence in human group interaction

by

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Tutors: Mario di Bernardo, Benoit Bardy, Cotutor: Pietro De Lellis

Ph.D. in Information Technology and Electrical Engineering

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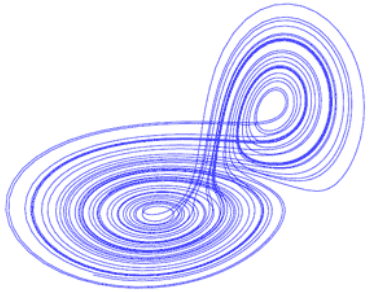
1 | Summary of my activities

General Information



- M. Sc. in Automation engineering in 2017
- PhD specialised in Analysis and Modelling in Complex Network
  scholarship from VINCI (UFI-IFU).

- Almost 5 months spent at University of Montpellier
  with Prof. Benoit Bardy

- Research products:
  - **2** journal papers (**+1** submitted),
  - **1** paper in preparation

Credits

Area	Year 1	Year 2	Year 3	Total
Courses	14	10	7	32
Seminars	6.4	4.4	0.2	11
Research	39	45	53	137

Publications

Journal papers:

1. [in preparation] Calabrese, De Lellis, Bardy, di Bernardo, “Capturing human slowing down during group interaction: modified Kuramoto models”.
2. [submitted] Calabrese, Lombardi, Bollt, De Lellis, Bardy, di Bernardo, “Self-emerging leadership patterns facilitate the onset of coordinated motion in human groups”, submitted.
3. Bardy*, Calabrese*, De Lellis, Bourgeaud, Colomer, Pla, di Bernardo, “Moving in unison after perceptual interruption”, Scientific Reports, 10(1), 1-13, 2020.
4. Della Rossa*, Salzano*, Di Meglio *, De Lellis*, Coraggio, Calabrese, Guarino, Cardona-Rivera, De Lellis, Liuzza, Lo Iudice, Russo, di Bernardo, “A network model of Italy shows that intermittent regional strategies can alleviate the COVID-19 epidemic”, Nature communications, 11(1), 1-9, 2020.

*These authors equally contributed

1 | Human group coordination

Background

- Man is by nature a social animal (Aristotle, "Politics“).

- Understanding how and why human beings interact in groups are key research questions across different scientific fields.

- Answering these paramount questions is challenging as interpersonal cooperation involves different levels of interactions.




State of the art on human group synchronization

- The daily situations where examples of human synchronization arise are varied and too complex.

- Promising approach: studying synchronization through platforms that simulate human behaviour in the task, to control and vary systematically the simulated partner's characteristics.

Possible applications

- Addressing this challenge is relevant for robotics.
- Coordination enhances social attachment and can then be used for rehabilitation of social disorders.
- **Autism** affects about 1% of the adult population with very high associated costs.
- Development of control-based cognitive platforms for group tele-rehabilitation able to assist medical staff, by promoting patients' participation, and to minimize distances, time and costs.

Contribution

- The main contribution is the experimental investigation, data analysis and modeling of group motor coordination and leadership emergence in human ensembles.

- **Open questions**:
  - understanding how individual and group features affect the group performance,
  - develop mathematical models able to capture and unfold the mechanisms underlying group coordination,
  - uncover from data if and how leaders naturally emerge to organise the synchronization onset and guide all other members towards a desired behaviour,
  - investigate if artificial agents interacting with human groups in a human-like fashion promote coordination and influence leadership emergence.

Mirror game

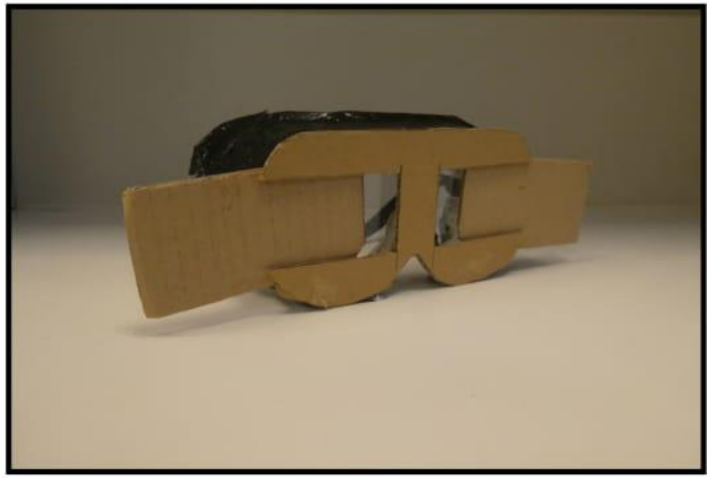
- Participants were engaged in a multi-player extension of a paradigmatic joint motor task, the mirror game, where players are involved in a simple hand movement coordination task, in space and time, when connected over different interaction patterns.

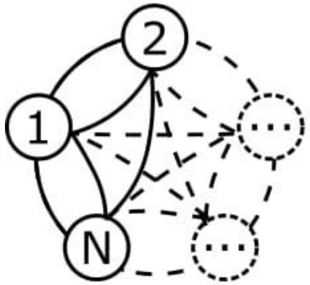
- This task was selected as it is extremely easy to learn and perform.

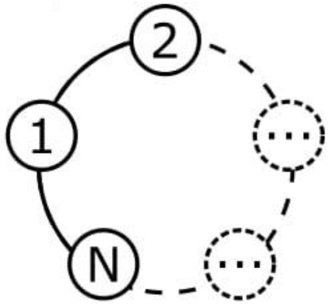
Mirror game- setups

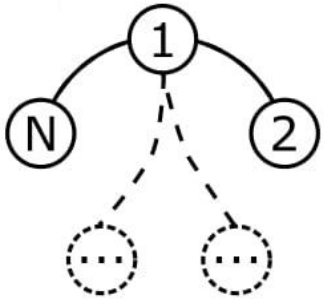
- **Setup 1- Pendula**
  - Visual feedback
  - Manipulating natural frequency





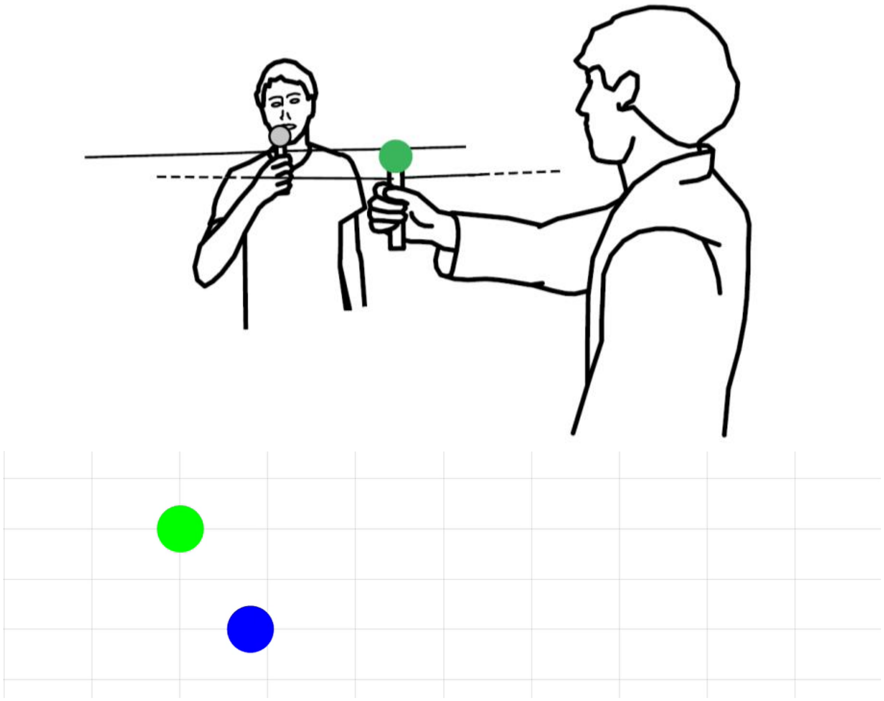


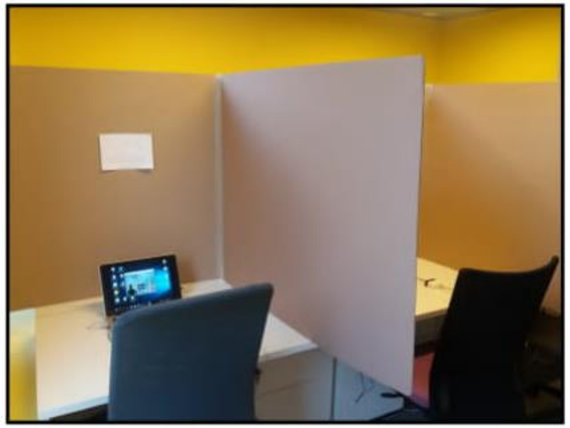


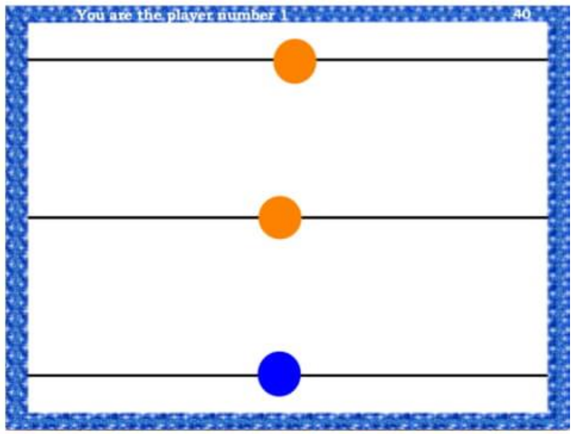


Mirror game- setups

- **Setup 2- Chronos**
  - Any visual feedback
  - Possible use of virtual agent





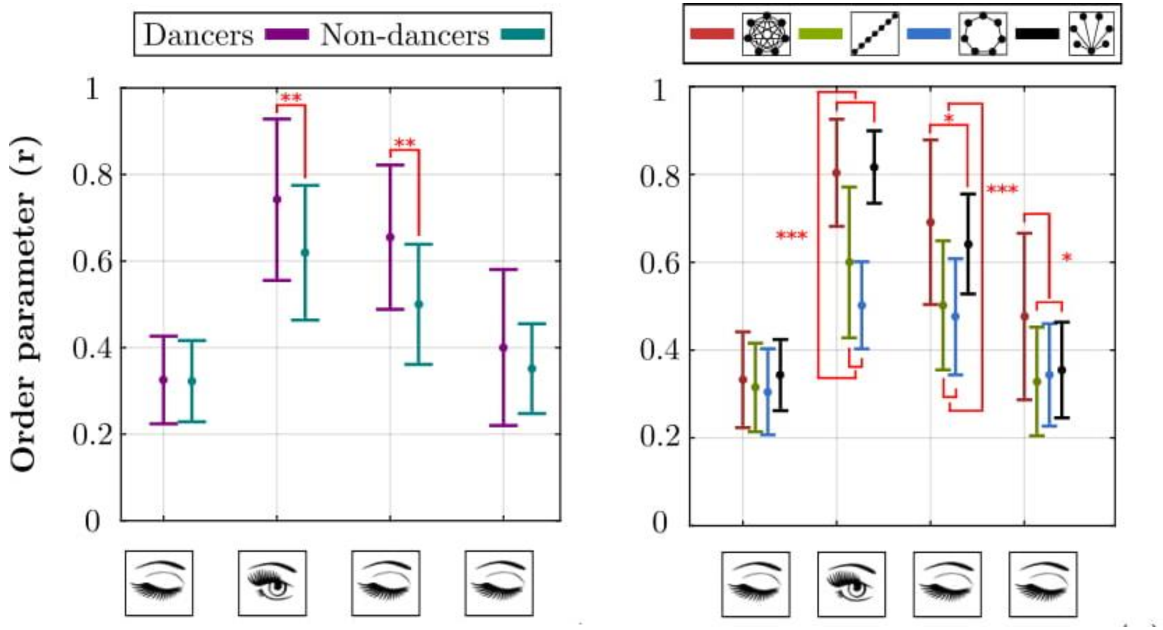


2 | Analysis of human group coordination and social memory

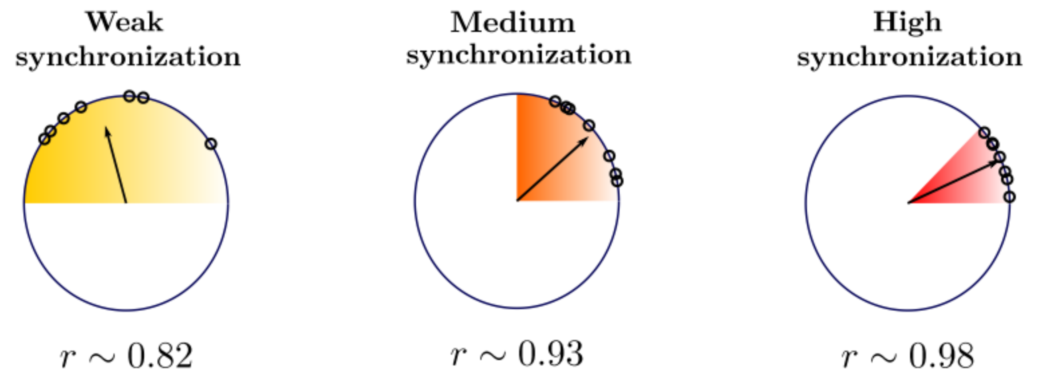
Analysis of human group coordination

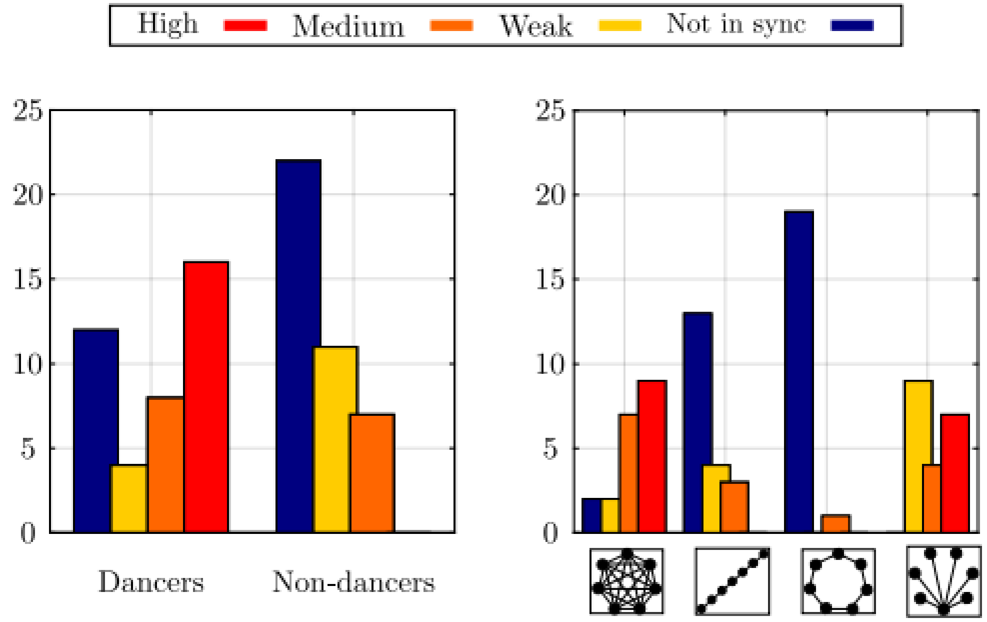
- We focused on the properties characterising interpersonal coordination among multiple agents:
  - expertise,
  - group spatial configuration,
  - amount of visual exchange.

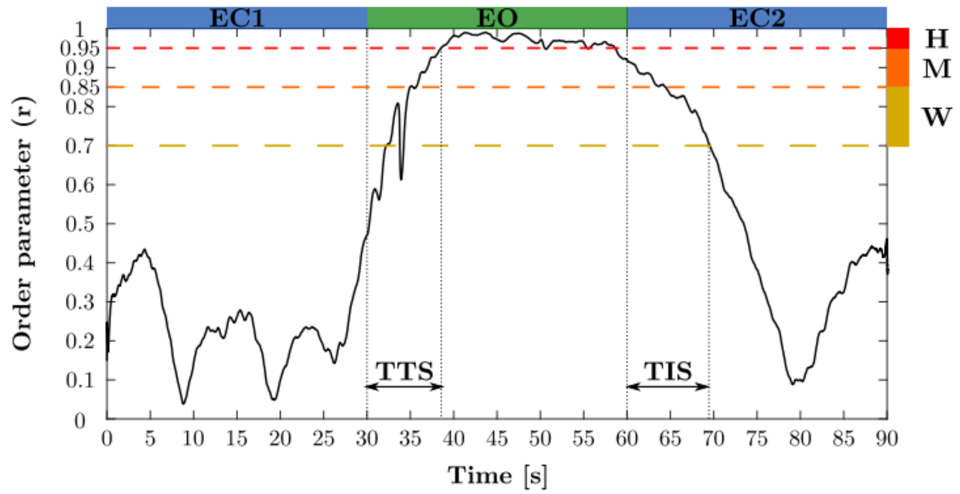
- Expertise in perceptuo-motor between participants synchronization facilitated synchronized behaviours, reinforced by specific configurations of the players in space.



Analysis of human group coordination







	Mean TTS	Mean TIS
Dancers	8.99 s	8.81 s
Non dancers	7.21 s	6.26 s

- We investigated the origin of this strong persistence of synchronization by introducing a memory effect in three different extensions of networks of Kuramoto oscillators.
- Coherence is maintained for a certain amount of time after visual exchanges were interrupted.

3

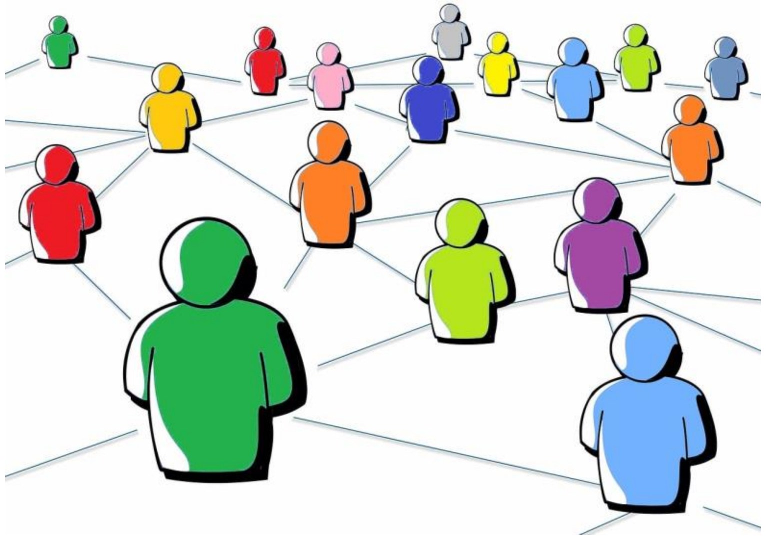
Capturing slowing down during group interaction

Modified Kuramoto models

Modelling

- Networks of heterogeneous Kuramoto oscillators successfully explain emergent synchronization in human groups performing oscillatory tasks.

$$\dot{\theta}_i = \omega_i + c \sum_{j=1}^{N} \sin(\theta_j(t) - \theta_i(t))$$



- It predicts synchronization to the average frequency of the individual characteristic frequencies, in contrast with our experimental observation that, **when synchronizing, the group tends to consistently reduce their average frequency.**

Slowing down

- Participants reduce the frequency of their oscillations when they try to coordinate with their partners:
  t(11) = 17.07, $p < 0.001$, **G1**;
  t(12) = 5.07, $p < 0.001$, **G2**;
  t(12) = 8.28, $p < 0.001$, **G3**.

Group 1		Group 2		Group 3	
Player #	$\overline{\omega}_i$ Solo	Player #	$\overline{\omega}_i$ Solo	Player #	$\overline{\omega}_i$ Solo
1	3.40 ± 1.55 rad/s	1	5.01 ± 0.23 rad/s	1	3.83 ± 0.26 rad/s
2	3.04 ± 0.11 rad/s	2	1.73 ± 0.64 rad/s	2	3.95 ± 0.23 rad/s
3	6.36 ± 0.58 rad/s	3	3.68 ± 0.49 rad/s	3	3.76 ± 0.47 rad/s
4	3.34 ± 0.21 rad/s	4	4.22 ± 0.14 rad/s	4	4.28 ± 0.30 rad/s
5	9.91 ± 0.68 rad/s	5	2.84 ± 0.20 rad/s	5	4.26 ± 0.36 rad/s
		6	6.39 ± 0.54 rad/s	6	3.54 ± 0.35 rad/s
Average	5.21 ± 2.96 rad/s		3.98 ± 1.64 rad/s		3.94 ± 0.29 rad/s

- This approach was successful since participants reached high synchronization level, different from chance.

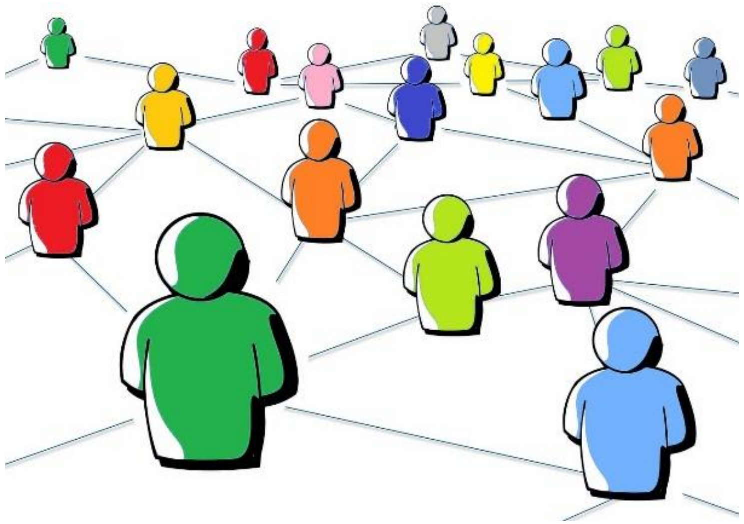
Group #	Group sync frequency ($\bar{\omega}_g$)	Order parameter (r)	Frequency sync index ($\bar{\rho}_g$)
1	2.97 ± 0.08 rad/s	0.90 ± 0.08	0.97 ± 0.01
2	3.23 ± 0.25 rad/s	0.78 ± 0.09	0.96 ± 0.03
3	2.88 ± 0.39 rad/s	0.78 ± 0.13	$0.98 \pm 5 \cdot 10^{-3}$

Neuroscientific hypotheses and proposed mathematical modeling

- The complexity of the processes underlying joint tasks lies in the interaction of several different mechanisms that allow individuals to observe and integrate the predicted effects of own and others' actions.

- We proposed three possible neuroscientific explanations of the slowing down with three corresponding extensions of the traditional Kuramoto model.

- Each modification acted on one of the three salient components of a complex system:
  - Agent dynamics
  - Adjacency metrics
  - Communication protocol



Neuroscientific hypotheses and proposed mathematical modeling

• Hypothesis 1

Precision and flexibility in the

$$\dot{\theta}_i = \omega_i(t) + c\sum_{j=1}^{N} \sin(\theta_j(t) - \theta_i(t))$$

$$\dot{\omega}_i(t) = \begin{cases} -\frac{1}{r^2(t)}\omega_i(t), & \text{if } r(t) < r_d, \\ 0, & \text{otherwise,} \end{cases}$$

pro-social behaviours and makes the agent more incline to adopt the ideology of the team.

Adaptivity is a key-aspect in cooperation tasks since each individual moves differently from everyone else.

Agent dynamics

• Hypothesis 2

Behavioural plasticity as the

$$\dot{\theta}_i = \omega_i + c\sum_{j=1}^{N} w_{ij} \sin(\theta_j(t) - \theta_i(t))$$

An act of … place, with mod… ative

$$w_{ij} = \frac{SD_i}{SD_j}$$

weight assigned to others (**selective attention**).

$$w_{ij} = \frac{SD_j}{SD_i}$$

We assu… …ts are related to motor variability, that is a result of compensation mechanisms to cope with perturbations, and facilitate changes in coordination patterns.

Adjacency matrix

• Hypothesis 3

Multilevel crosstalk represents

$$\dot{\theta}_i = \omega_i + c\sum_{j=1}^{N} \sin(\theta_j(t-\tau) - \theta_i(t))$$

Since any natural process is not instantaneous, a motor model should incorporate time **delays**, which induce temporal coupling between functional elements to modulate perception and stabilize coordination.

Communication protocol

Tuning and validation

- The delayed model is tl $\Pi_m^* = \arg\min_{\Pi_m} J_g(\Pi_m), \quad \forall m \in \{1, 2a, 2b, 3\}$ alue of the cost function)

$$J_g(\Pi_m) = \left(\frac{\overline{\omega}_{g,exp} - \overline{\omega}_{g,sim}(\Pi_m)}{\overline{\omega}_{g,exp}}\right)^2 + \lambda\left(\frac{\overline{r}_{exp} - \overline{r}_{sim}(\Pi_m)}{\overline{r}_{exp}}\right)^2 + (1-\lambda)\left(\frac{\overline{\rho}_{exp} - \overline{\rho}_{sim}(\Pi_m)}{\overline{\rho}_{exp}}\right)^2$$

		Model 3
Group1	F(	).04 ± 0.02
Group2	F	).03 ± 0.02
Group3	F	).05 ± 0.03

- Joint action requires a more selective and slower mechanism compared to individual movements. The temporal difference between interacting partners is necessary to gain time to see and judge what the other person does during joint interaction.

4 | Leadership emergence during coordinated motion in groups

Leadership in human groups

- Leadership emergence is one of the most interesting and important questions in human behaviour.



- It is a solution to specific social group coordination challenges, such as group migration or inter-group competition, necessary to guide the group and to take collective decisions.

Leadership in human groups

- **Who we are is how we lead-** several definitions of human leadership have been proposed focusing mostly on isolated variables that describe personality aspects that characterize a leader.

- Part of the literature <u>rejects a person-centric and hierarchical approach</u>.

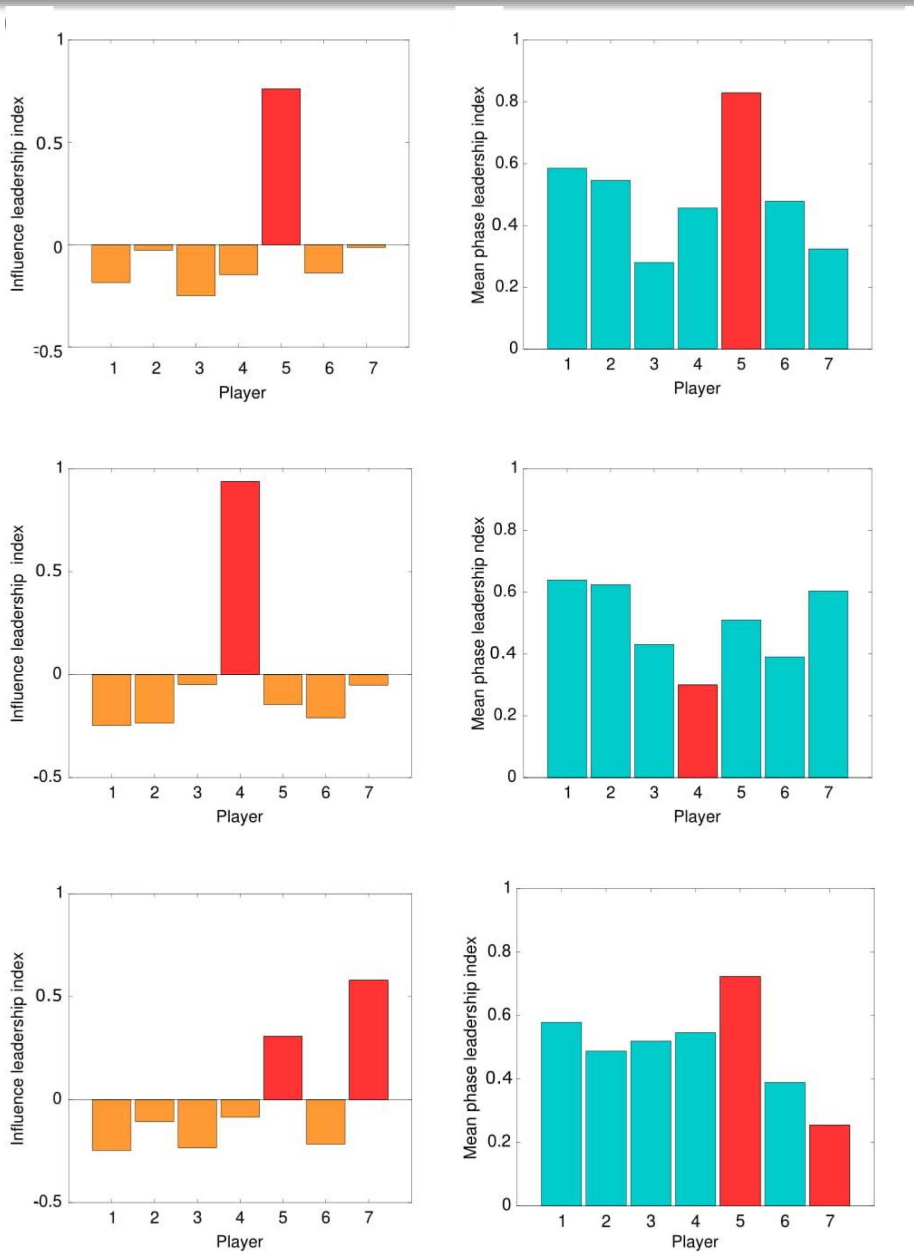
- Leadership is a **collective phenomenon-** individuals co-construct identities as leaders and followers. Over time, these **leader–follower relationships emerge to form group-level leadership structures** that can evolve to enable groups to adapt in dynamic environments.

Leadership patterns

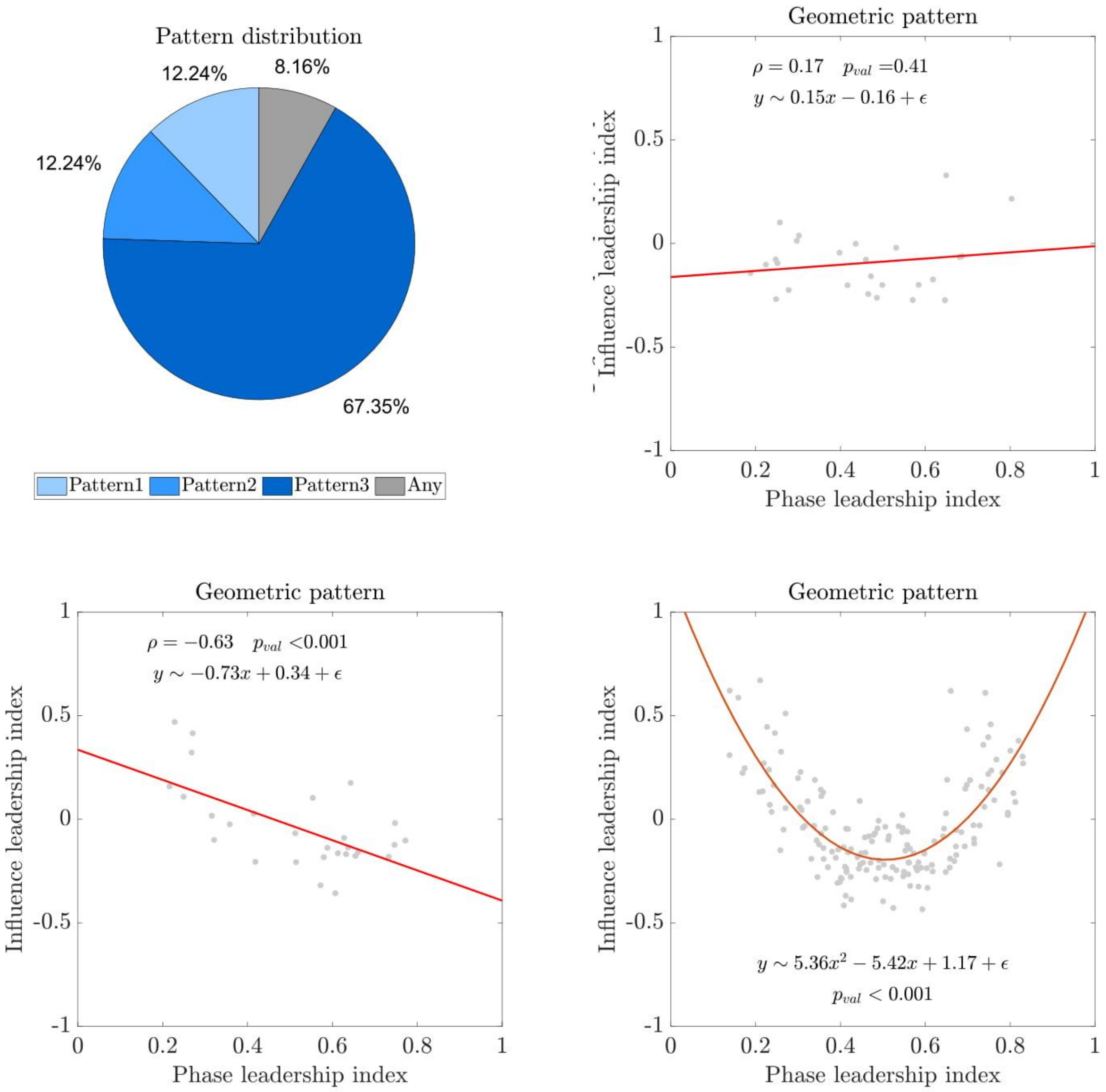
- We focused on the problem of studying leadership emergence and its effects in human groups involved in a joint motor task.

- By means of a combined use of two metrics- phase leadership and net causation indices-, we uncovered three main patterns through which leadership emerges.

- These three scenarios can be related to some team sports.



Leadership in human groups



- Leadership emergence does foster coordination.

- These observations were independent of the presence of physical perceptuo-motor interaction among the players.

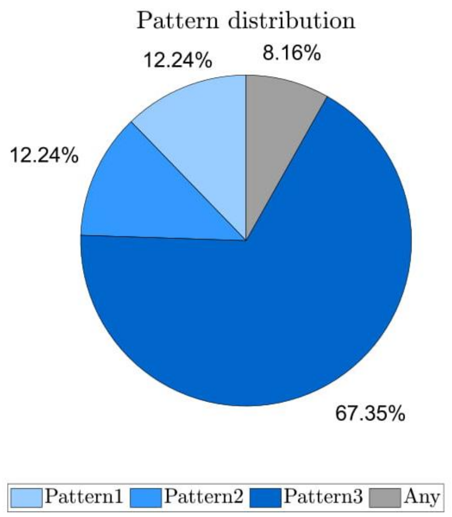
- The results were validated and confirmed via a set of experiments with Chronos, in the absence of social interaction.

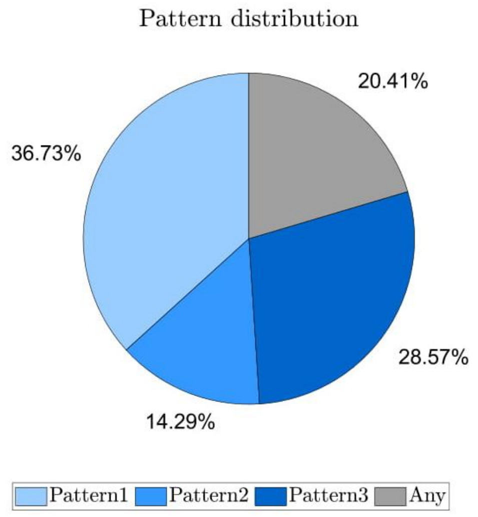
Influence of a virtual player on leadership emergence

- Preliminary investigation of the influence of a virtual player interacting within a human ensemble on the levels of group synchronization and leadership emergence.

- Virtual players with specific kinematic characteristics, appropriately connected to a participant in the ensemble, were found to be able to influence both group coordination and leadership emergence.

Without VP

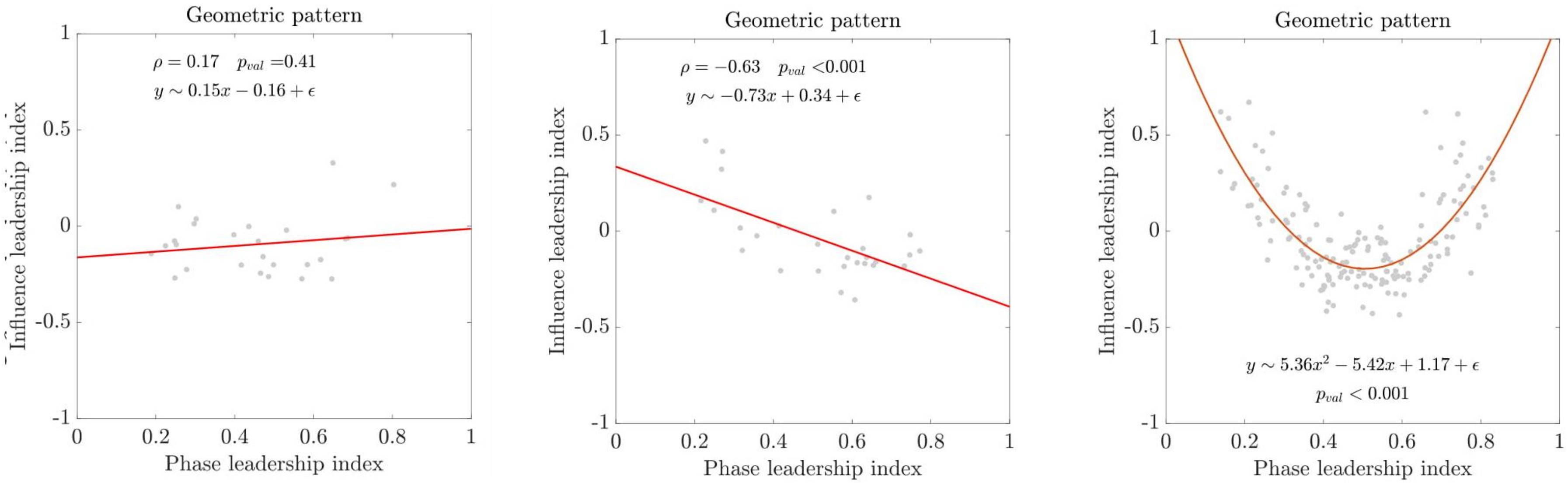




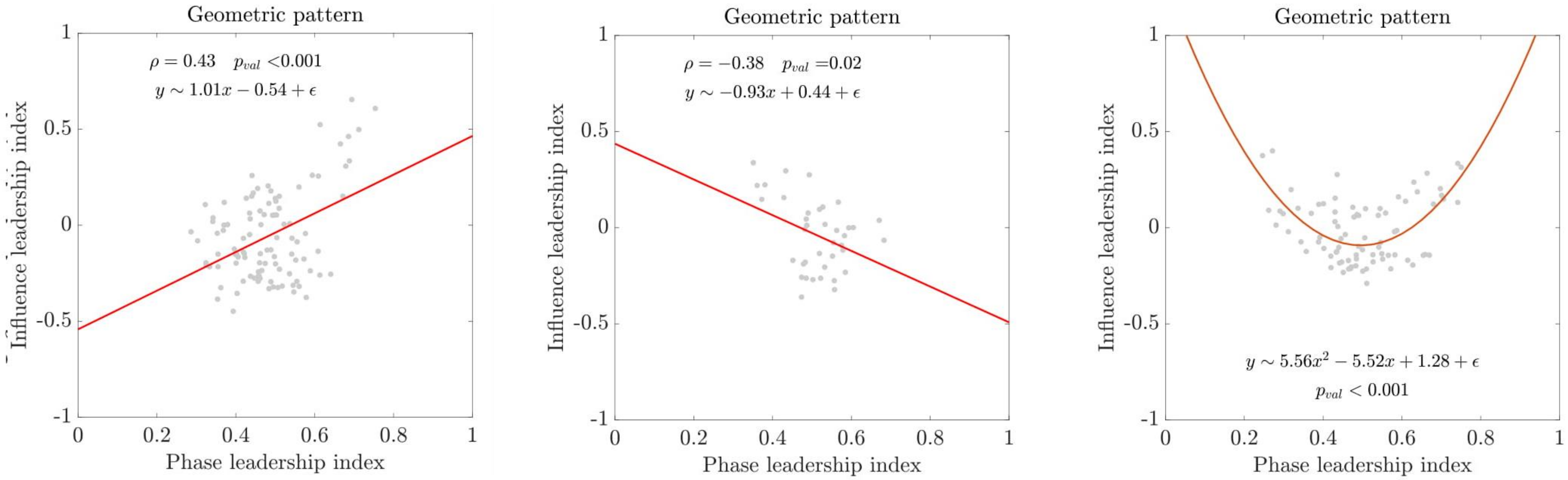
With VP

Influence of a virtual player on leadership emergence

Without VP



With VP

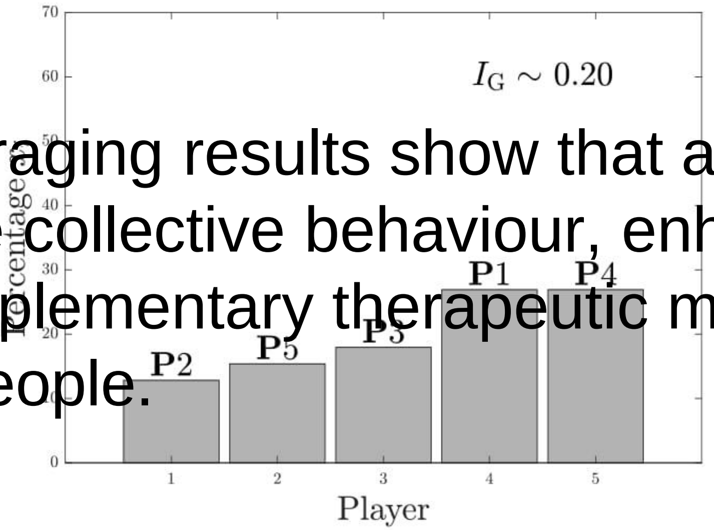


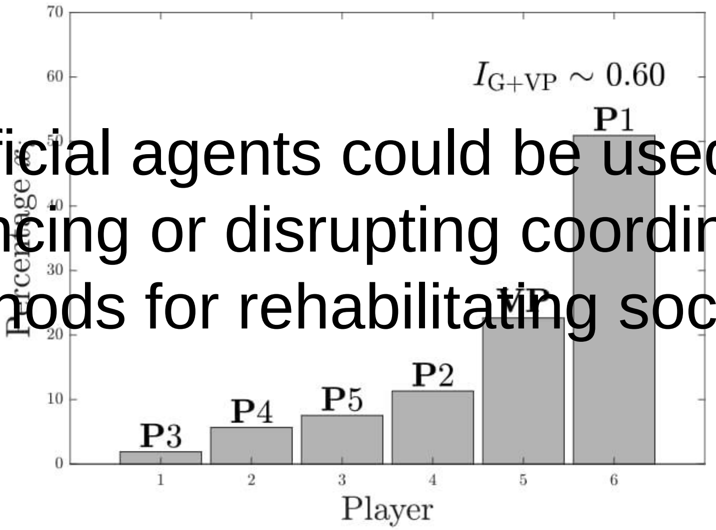
Distribution of leader role across players

- Authors posited the existence of diverse leadership structures, from centralized to distributed leadership structure.

- The identity of the leaders emerging in the patterns was not always the same.

- The Gini index helped to discriminate the emergent leadership structure.





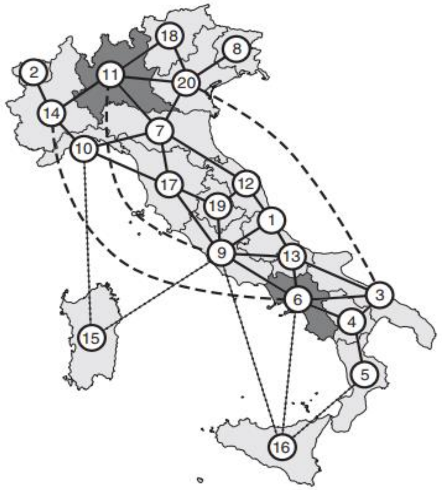
- These encouraging results show that artificial agents could be used to influence and guide the collective behaviour, enhancing or disrupting coordination and could be complementary therapeutic methods for rehabilitating socially challenged people.

Conclusions

- Human coordination is a complex yet fascinating phenomenon common to a large number of different human activities.

- By means of a combination of analytical, experimental, and numerical tools, this work addressed the following key research questions:
  1. establish how the interaction patterns and the individual dynamics affect the coordination level of the ensemble;
  2. propose mathematical models to capture and analyse group coordination;
  3. analyse formally and quantitatively how leadership in human group motor synchronization emerges through group interactions;
  4. explore whether levels of group cohesiveness and leadership agency distribution can be influenced by introducing some virtual players in the group.

Two collaborations



- [illegible] alleviate the epidemic impact on both [illegible] avoiding saturation of the regional health systems.
- [illegible] aggregate, ignoring [illegible] likelihood of generating [illegible] infected.

- **INSIST** - Sistema di monitoraggio **IN**telligente per la **SI**curezza delle infra**ST**rutture urbane

- **Goal**: innovation in monitoring systems on critical structures in urban areas, in particular on **bridges**, by attributing a certain degree of computing capacity to all levels of the system to have a real-time damage detection.

Publications

Journal papers:

1. [in preparation] Calabrese, De Lellis, Bardy, di Bernardo, “Capturing human slowing down during group interaction: modified Kuramoto models”.
2. [submitted] Calabrese, Lombardi, Bollt, De Lellis, Bardy, di Bernardo, “Self-emerging leadership patterns facilitate the onset of coordinated motion in human groups”, submitted.
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Thank you for your attention.

Questions?

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