Nonverbal leadership emergence in walking groups

Maria Lombardi[1,2], William H. Warren[3,*], and Mario di Bernardo[1,2,*]

[1]Department of Engineering Mathematics, University of Bristol, Bristol, UK
[2]Department of Electrical Engineering and Information Technology, University of Naples Federico II, Naples, Italy
[3]Department of Cognitive, Linguistic and Psychological Sciences, Brown University, Providence, RI 02912, USA
[*]Corresponding authors: bill_warren@brown.edu, m.dibernardo@bristol.ac.uk

ABSTRACT

Understanding the mechanisms underlying the emergence of leadership in multi-agent systems is still under investigation in many areas of research where group coordination is involved. While leadership has been mostly investigated in the case of animal groups, only a few works address the problem of leadership emergence in human ensembles, e.g. pedestrian walking, group dance. In this paper we study the emergence of leadership in the specific scenario of a small walking group. Our aim is to propose a rigorous mathematical methodology capable to unveil the main mechanisms emerging in a human group when leader or follower roles are not designated a priori. Two groups of participants were asked to walk together and turn or change speed at self-selected times. Data were analysed using time-dependent cross correlation to infer leader-follower interactions between each pair of group members. The results indicate that leadership emergence is due both to contextual factors, such as an individual's position in the group, and to personal factors, such as an individual's characteristic locomotor behaviour. Our approach can easily be extended to larger groups and other scenarios such as team sports and emergency evacuations.

Introduction

A number of interesting phenomena can emerge from the collective behaviour of a group of agents interacting with each other that cannot be explained in terms of the dynamics of an individual agent[1,2]. One phenomenon of extreme importance is the emergence of leadership. Leadership plays a crucial role in determining the success or the failure of a variety of activities both in animals (e.g. protecting the animal group against predatory attacks, locating food resources) and human groups (e.g. steering opinion dynamics, playing music or sport). Many studies exist in the literature addressing coordination and leadership emergence in the case of groups of animals[3–7], where the problem is tackled by studying how agents informed about a migration route or food position influence collective behaviour. In this context, results shows that, as group size becomes larger, only a small proportion of informed individuals is needed to guide the group behaviour.

In the case of human groups, several studies investigated the problem of emergence of leadership from a psychological or anthropological point of view[8–11]. For example, the choice of leading a group may be taken often by individuals who put a high value on decision rights or who desire to control others' outcomes[12,13]. On the other hand, the leader role can be seen as a burden and so avoided by individuals acting mostly as followers[14]. Dominance versus egalitarianism allows to make different predictions about the personalities of individuals emerging as leaders in formerly leaderless groups. Indeed, dominance-view leadership is expected to correlate with selfish and egoistic traits whereas egalitarianism-view leadership is expected to correlate with pro-social personality traits[9,10].

Contrarily, limited results are available on leadership emergence in situations where nonverbal communication is essential. Examples include the role of a conductor in an orchestra[15,16], group behaviour in dance[17,18], consensus decision making with informed and non informed individuals[19–21], but only little quantitative analysis is carried out on mathematical modelling the phenomenon of leadership and the interaction patterns established within a group[22,23].

Here, we study the emergence of leadership in a group of people walking together[24–27]. The goal is to propose a rigorous mathematical methodology capable to assess whether leadership emerges and whether it facilitates group coordination and cohesiveness. Understanding leadership emergence in groups of humans walking together can be relevant in many applications. For example, during evacuation from a building, the presence of a leader with global knowledge of the structure can safely guide people towards the exit avoiding fatal consequences[28]. Emergency situations are often characterised by high complexity, uncertainty, chaos, and ambiguity, thus requiring a coordinated and synchronised collective action. In such situations, leader identification is a crucial task to steer the group towards a desired collective behaviour. By finding, influencing or disconnecting the leaders from the rest of the crowd, efficient containment strategies can be accomplished[29]. Other applications may be the analysis of pedestrian flows in a shopping centre identifying crowd patterns and cluster formation, or preventing that violent behaviour conducted by a small part of fanatic supporters at a football match can spread among the crowd.

Past studies have observed that, in these situations, some people have a higher probability of becoming leaders according to

their attitude or qualities, e.g. ability to handle emergence situations, charisma, confidence, friendliness, effective speaking[30]. Another interesting attitude that may play an important role in this context is the willingness of few individuals to shoulder responsibility and take common decisions affecting and so the responsibility aversion of the majority[14]. Also, it has been observed that such a leader is characterised by specific behavioural or physiological traits such as a common tendency to act first[31]. On the other hand, the spontaneous emergence of leadership may depend on contextual factors, such as an individual's position in the group[6].

To investigate leadership emergence in human groups, we consider the simplest scenario in which four participants are asked to walk together across the room. Our aim is to unveil whether, when no designated roles are assigned, a leader emerges in the group. Specifically, we adopt a time-dependent cross correlation analysis to unfold the leader-follower relationships established within the group by instructing all participants to change their heading direction or speed twice at their will during every trial. We then analyse each trial to identify the individual whose change of locomotion (direction or speed) is readily followed by other group members. That individual is then labelled as the leader on that trial. We further analyse how relative positions in the group, or a participant's characteristic locomotion behaviour, influence leadership emergence.

Our findings serve as *proof of existence* of different types of leadership emerging from walking crowds. Precisely, we identify an "emergent leaderhip"scenario depending on local visual couplings between group members that try to match their speed and heading direction accordingly, confirming the observations made in[25, 26, 32]. Also, our data analysis identifies an "individual leadership" type showing that in some situations a participant's characteristic locomotion behaviour can be so influential as to dominate the group independent of his/her position.

Results

Two groups of four participants were tested during the experiment, designated Group 1 and Group 2. Before each trial, group members were positioned on the vertices of a square configuration, labelled as FL (front left), FR (front right), BL (back left) and BR (back right) (refer to *Methods*, Figure 4). To identify an individual participant, we use the notation "P*x.y*" where *x* is the group and *y* is a sequential number identifying a specific participant, for example P1.3 indicates participant 3 in group 1. During each trial, group members were instructed to change direction (turn left/turn right) or speed (speed up/slow down) twice while staying together as they walked across the room. Three different initial inter-personal distances (IPD) between participants were tested: 1, 2 and 4 metres. Participants' positions were shuffled between each trial.

The data were analysed to assess the effect on leadership emergence of (i) spatial position in the group and (ii) individual locomotor behaviour. We compared the time series of heading (or speed) for each participant by adapting the time-dependent cross correlation metric proposed in[33] to characterise leadership emergence in groups of trawling bats. Briefly, the method quantifies the temporal dependence of turns (or speed changes) between group members, allowing us to compute an *individual leadership index* for each participant on each trial (for further details and formal definition of the index see *Methods*).

Effect of pedestrian position in the group

Due to the square configuration used during the experiments, we expected one of the pedestrians in the front row to act as the leader because they can influence participants in the back row (i.e. the back row is visually coupled to the front row), but not vice versa.

Figure 1 shows the influence of participants' position on the *individual leadership index*, averaged over all trials, in the two conditions (heading direction and speed). Results indicate that participants in the front left and front right positions have the highest value of the leadership index.

This is confirmed by a formal statistical analysis. A three-way Mixed ANOVA (2 Conditions × 4 Positions × 3 IPD) was performed on percent leadership, in which Condition and IPD were treated as "between-subjec" factors, Position was treated as a "within-subject" factor, and Group was considered a random effect. The analysis revealed a significant main effect of Position on the measured leadership ($F(3,117) = 19.865, p < 0.05, \eta^2 = 0.337$).

The Condition main effect and the Condition × Position interaction were not in themselves significant, having respectively $F(1,39) = 1.334, p = 0.255, \eta^2 = 0.033$ and $F(3,117) = 0.196, p = 0.899, \eta^2 = 0.005$, indicating a similar influence of position on leadership for heading and speed. Furthermore, neither the IPD main effect ($F(2,39) = 0.133, p = 0.876, \eta^2 = 0.007$) nor the IPD × Position interaction ($F(6,117) = 0.906, p = 0.493, \eta^2 = 0.044$) were significant, indicating a similar influence at all distances.. Finally, the three-way Condition × IPD × Position interaction was not significant, $F(6,117) = 1.301, p = 0.262, \eta^2 = 0.063$. Thus, the factor Position alone dominates percent leadership.

Since the factor Position was statistically significant, we performed Bonferroni post hoc test for a pairwise comparison in order to understand in detail what positions influence most leadership emergence. We found that the differences between the front positions and the back positions are statistically significant ($p < 0.05$) while the differences between the two positions in
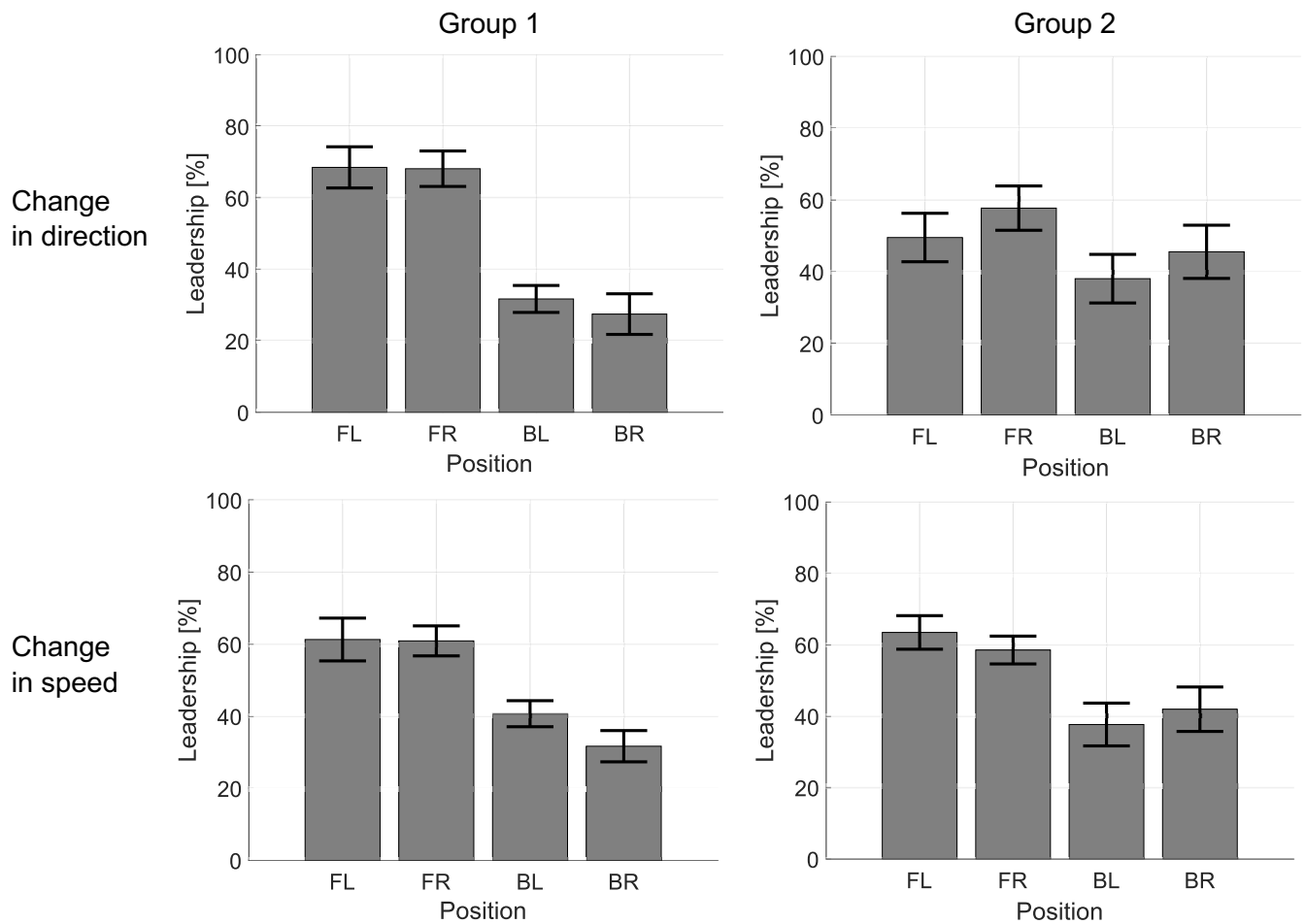
Figure 1. Averaged percent leadership evaluated grouping the trials by position. Four bar charts are reported, 2 groups × 2 condition (speed and heading direction). Each bar represents the mean value of the leadership grouped by position over the number of trials, whereas grey error bars are the standard error of the mean. FL = front left, FR = front right, BL = back left, BR = back right.

the front and between the two in the back have a $p = 1$ and so not statistically significant. These results demonstrate a clear contextual effect of position on emergent leadership.

Effect of individual locomotor behaviour

The same data are replotted by participant in Figure 2, where the mean value and standard error of the mean (SEM) of the individual leadership index are shown for each pedestrian. Notice that some participants have consistently higher indices than the others. A one-way ANOVA (4 Participants) on mean percent leadership was performed separately for each group revealing a main effect only in direction-change trials for Group 2 ($F(3,24) = 4.663, p < 0.05, \eta^2 = 0.368$).

In these trials, pedestrian P2.4 became the leader independently of his/her position in the group as shown in Figure 3 (details about leader-follower patterns inferred from the data are reported in *Supplementary Info, Supplementary Figures 1,2,3 and 4*). Pairwise comparisons of participant means using a Bonferroni post-hoc test confirmed that the behaviour of pedestrian P2.4 has a significant influence on the behaviour of the whole group ($p < 0.05$). This influence is absent in the speed-change condition.

We attribute the leadership of pedestrian P2.4 to a characteristic behaviour, the tendency to initiate a change by acting first, which is evident in the time series (see *Supplementary Info, Supplementary Figures 1,2,3 and 4*). The question arises, however, as to how this individual could influence other group members from the back row when changing direction, but not when changing speed. This discrepancy may be explained by the observation that on direction-change trials, P2.4 often moved into the peripheral field of view of other group members, whereas on speed-change trials, P2.4 remained directly behind the front row, out of view.
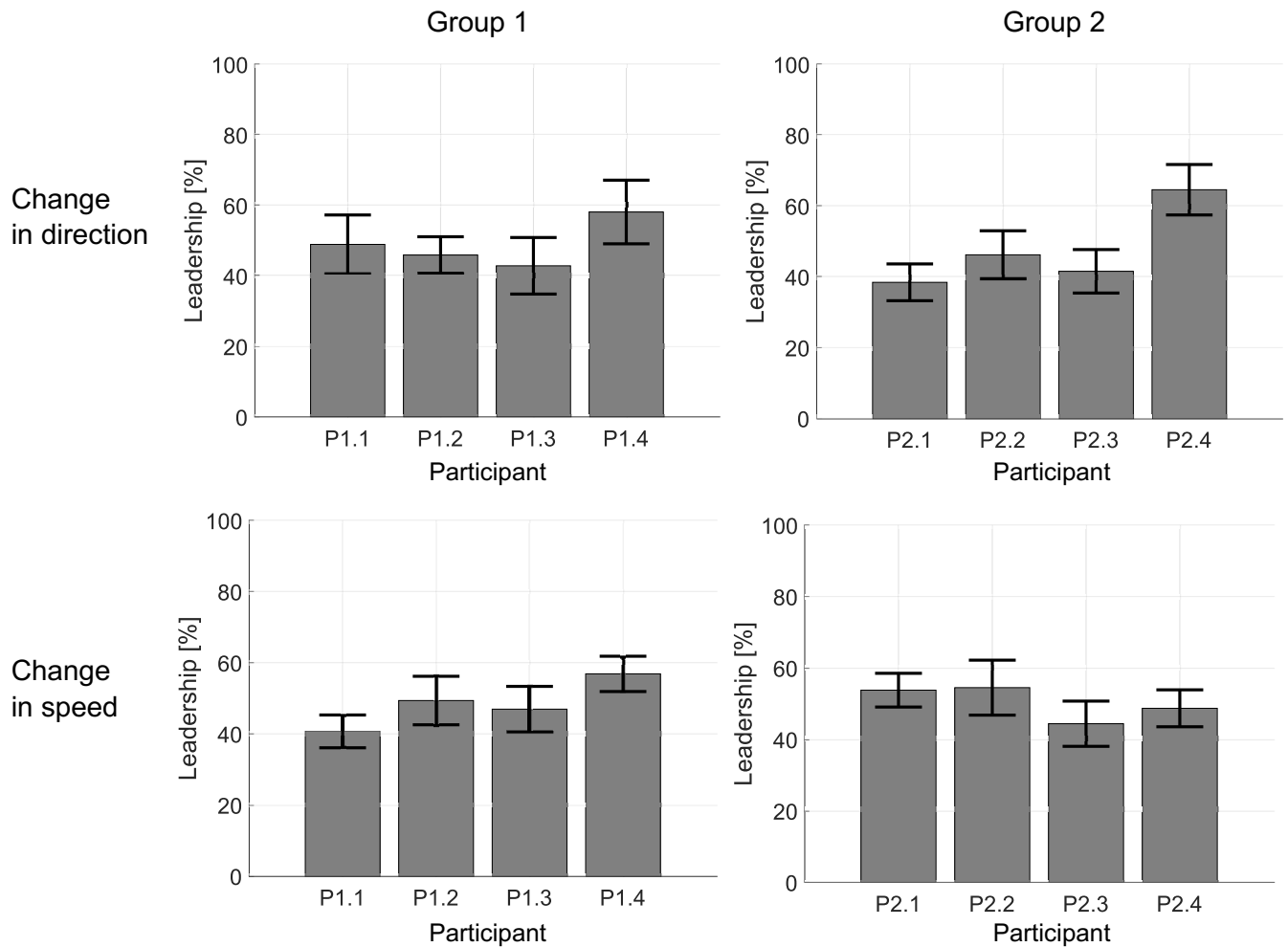
Figure 2. Averaged percent leadership grouping the trials by individual pedestrian. Four bar charts are reported, 2 groups × 2 condition (speed and heading direction). Each bar represents the mean value of the leadership grouped by a specific pedestrian over the number of trials independently from his/her position, whereas grey error bars are the standard error of the mean.

Discussion

In this work, we carried out a data-driven experimental investigation of leadership emergence in a group of walking pedestrians. Two groups of four volunteers each were asked to walk across a room together, and to change their heading or speed. We then analysed the acquired data on their movement and speed by defining a novel "individual leadership index" to identify the leading participant and reconstruct leader-follower interactions in the group. This metric is based on time-dependent correlation analysis and was adapted from the indexes[33] that were used previously to study the leader-follower behaviour of flying bats. To the best of our knowledge, it is applied here for the first time to a human group in order to predict leader-follower patterns.

Our analysis shows that both contextual factors, such as the position of an individual in the group, as well as personal factors, such as a characteristic locomotor behaviour, contribute significantly to the emergence of a leadership role. In particular, our findings confirm that participants in the front row, to whom those in the back row are visually coupled, are usually elected as leaders via the mechanism of collective motion, in which pedestrians match the heading direction of neighbours in their field of view[24]. However, we also find that a specific individual assumed a leadership role more than 60% of the time, initiating a change in direction irrespective of their position in the group. By deciding to turn first, this participant exploited the mechanism of collective motion to seize the leadership, a *self-appointed* leader.

These findings demonstrate that leadership in walking groups is a complex phenomenon that does not only depend on geometric conditions, such as the leader location in the group (emergent leadership), but also on other features related to the characteristics of individual participants (individual leadership); for example, the tendency to initiate movements or changes of direction that when perceived by neighbours propagate to the rest of the group. This observation might be relevant to understand
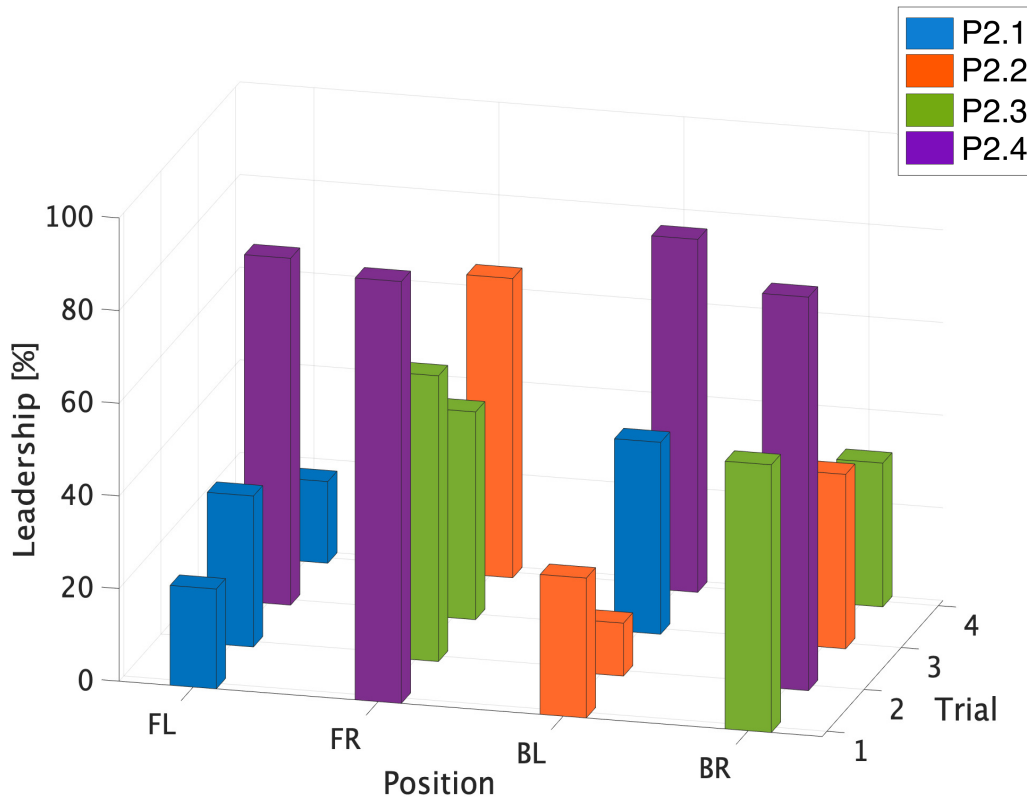
Figure 3. Percent leadership of four sample trials having P2.4 in each position. Percent leadership of four sample trials are reported having the pedestrian P2.4 (in purple) in each of position. The *x*-axis represents the trial, the *y*-axis the position (Front Left, Front Right, Back Left, Back Right), whereas the *z*-axis reports the value of leadership in percentage. Each pedestrian is identified by different colour.

how coordination in walking groups emerges in situations, such as emergency evacuations or some sport scenarios, where verbal communication among group members is limited. Of course, these observations need to be further investigating with additional experiments that are beyond the scope of this paper which is focused on presenting the methodology.

We wish to emphasise that the present methodology reveals information about specific leader-follower relationships within a group and how they change over time, as illustrated in Figures 5 and 6. Moreover, the method can be generalised to larger pedestrian groups and other scenarios. An understanding of leadership emergence and the factors on which it depends can be extremely useful in emergency situations when it is critical to influence group dynamics, such as guiding a crowd to a safe exit.

Methods

Experiment
Participants.   Two groups of 4 participants were tested in separate sessions as part of a larger study. The research protocol was approved by Brown University's Institutional Review Board, in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants, who were compensated for their time. All participants had normal or corrected vision, and none reported a motor impairment.

Task and procedure.   Before each trial, participants were positioned at the vertices of a square configuration marked on the floor ("front left" (FL), "front right" (FR), "back left" (BL), "back right" (BR)), at one of three initial inter-personal distances (IPD of 1, 2, or 4m) (see Figure 4). They were instructed to change direction or speed twice at self-selected times as they walked together across the room (about 20m), and to "try to stay together with your neighbours". There were nine possible instructions: change direction in left/right sequence (LL, RR, LR, or RL), change speed in low/fast sequence (SS, FF, SF, or FS), or no-change control (CC). The experimental design was thus 2 Conditions (heading direction, speed) × 4 Sequences × 3 IPD (1, 2, 4 m), with one trial in each of the 24 conditions plus three control trials. Given that no effects of IPD were found,

data were collapsed across sequence and IPD for analysis, yielding 12 trials per analysed condition.

At the beginning of each trial, a sequence instruction was given, then the group started walking upon a verbal "ready, begin" command. Before the next trial, participants shuffled their positions in the starting configuration. Each group received one practice trial, followed by a block of 12 heading change trials, and a block of 12 speed change plus 3 control trials, for a total of 27 test trials. Trial order was randomised within blocks, and block order was counterbalanced across the two groups. A test session lasted about 40 min. Further details about each single trial are reported in *Supplementary Info, Supplementary Tables 1 and 2*.
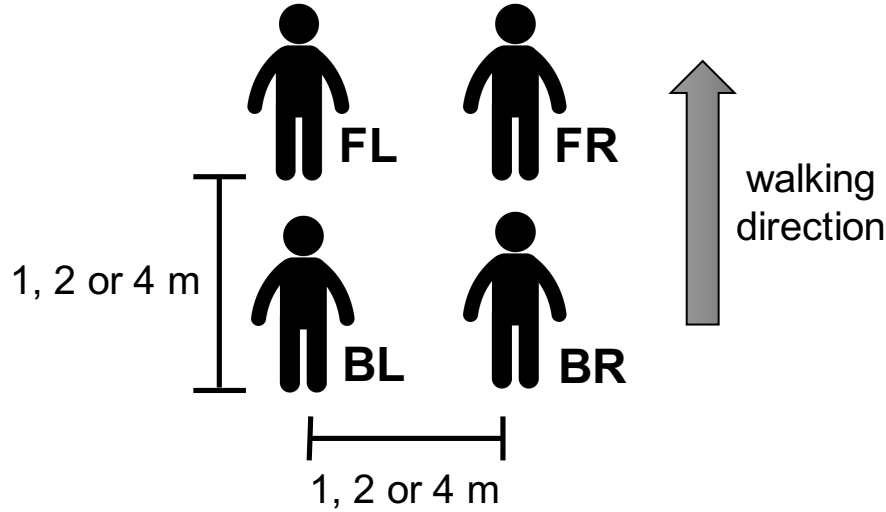

Figure 4. Group configuration. Participants are placed at the vertices of a square (FL, FR, BL, BR) with an initial inter-personal distance (IPD) between them of 1, 2 or 4 metres.

Data acquisition and analysis

The experiments were carried out at Brown University in a large hall with a 14m × 20m tracking area marked on the floor. Head position was recorded at 60 Hz with a 16-camera infrared-reflective motion capture system (Qualisys Oqus). Each participant wore a bicycle helmet having 5 markers placed on $30-40$cm stalks in a unique configuration, so that each helmet could be identified.

The time series of head positions of all four pedestrians were recorded in three dimensions, but only two dimensions (*xy*-plane) were analysed further. Time series were filtered using a forward and backward 4th-order low-pass Butterworth filter to reduce tracker error and gait oscillations, before differentiating to obtain time series of speed and heading. A 1.0 Hz cutoff was used to reduce anterior-posterior oscillations on each step before computing speed, and a 0.6 Hz cutoff for reducing medial-lateral oscillations on each stride before computing heading. Files were truncated to eliminate endpoint error. Leadership was then evaluated by assessing the difference in heading direction at each time between each pair of pedestrians by adapting the time-dependent delayed directional correlation C^d (see *Leadership metrics*)[33]. Summing the percentage of time in which a specific pedestrian is identified as leader, we were able to reconstruct a network representing the influence that a specific pedestrian has on any other. Similarly, leadership in speed was evaluated by adapting the previous algorithm using time-dependent delayed speed correlation C^s instead.

Leadership metrics

Time-dependent delayed directional correlation (TDDC). Using time-dependent delayed directional correlation (TDDC), we characterised leadership in the walking group in terms of the heading direction of each individual, spotting whether some of the participants adjusted their own direction to that of the others and exhibited a follower role. Accordingly, a leader is defined as the participant whose heading direction influences the others the most, in the sense that the other participants match their headings with that of the leader after a time delay corresponding to the natural human visual-locomotor delay.

Denoting by $v_k \in R^2$ the velocity vector of pedestrian k in the plane, we compute:

$$h_{ij}(t,\tau) = \frac{v_i(t)}{||v_i(t)||} \frac{v_j(t+\tau)}{||v_j(t+\tau)||} \quad \in [-1,1], \tag{1}$$

which represents the scalar product between the heading direction of pedestrian i at time t and that of pedestrian j at delayed time $t + \tau$.

Formally, TDDC is defined as follows:

$$C_{ij}^d(t, \tau) = \frac{1}{2\omega + 1} \sum_{k=-\omega}^{\omega} h_{ij}(t + k\Delta t, \tau),$$ (2)

where Δt is the sampling time and $\omega > 0$ is a suitably selected constant. In order to compensate for high-frequency noise and measurement errors, $h_{ij}(t, \tau)$ is averaged over a symmetric time-window $2\omega\Delta t$. As the measured human visual-locomotor delay to the leader's change in heading is approximately equal to 1000 ms and the sampling time for the collected data is equal to $\Delta t = \dfrac{1}{60Hz}$, we have that $2\omega\Delta t > 1s$ and so ω was set to 40.

To identify the leader, $C_{ij}^d(t, \tau)$ was evaluated for each pair of pedestrians (i, j) at every time instant t along the trial and for different values of delay τ. If the value of $\tau_{ij}(t)$ maximising the heading direction correlation is positive then we say that pedestrian i leads pedestrian j at time instant t, or otherwise if that value is negative.

A left-right trial carried out by Group 1 with an initial IPD of 4m is taken as a representative example to illustrate the analysis based on time-dependent directional correlation metric. Figure 5(d) shows the heat maps characterising values of $C_{i,j}^d(t, \tau)$ for the whole duration of the trial with different time delay τ between each pair (i, j) of pedestrians.

Time-dependent delayed speed correlation (TDSC).   To assess leadership roles in speed-change trials, we define:

$$\Delta s_{ij}(t, \tau) = \big| \, ||v_i(t)|| - ||v_j(t + \tau)|| \, \big|$$ (3)

which represent the difference between the speed of pedestrian i at time t and that of pedestrian j at delayed time $t + \tau$. The time-dependent speed correlation (TDSC) is defined as:

$$C_{ij}^s(t, \tau) = \frac{1}{2\omega + 1} \sum_{k=-\omega}^{\omega} \Delta s_{ij}(t + k\Delta t, \tau),$$ (4)

where the parameter ω is the length of the symmetric window used to average $s_{ij}(t, \tau)$ in order to compensate for noise and measurements errors as done before. As the measured human visual-locomotor delay to the leader's change in speed is approximately equal to 500 ms[26], we have set ω to 20. In this case pedestrian i is said to lead pedestrian j at time t if the value of $\tau_{ij}(t)$ minimising the speed correlation is positive, or otherwise if it is negative.

A fast-slow trial carried out by group 1 with an initial IPD of 2m is taken as a representative example to illustrate the analysis of the data based on time-dependent speed correlation metric. Figure 6(d) shows the heat maps characterising values of $C_{i,j}^s(t, \tau)$ for the whole duration of the trial with different time delay τ between each pair (i, j) of pedestrians.

Individual leadership index.   Knowledge of $\tau_{ij}(t)$, maximising/minimising the heading direction/speed correlation, for each trial and pair of pedestrians allows to quantitatively estimate how much a participant acts as a leader in the group. Specifically we define the *individual leadership index* for each participant as the overall average percentage of time for which the computed $\tau_{ij}(t)$ is positive (Figure 5(e) and Figure 6(e)).

Network reconstruction.   Knowledge of $\tau_{ij}(t)$ allows also to infer leader-follower interactions between each pair of group members. Each pedestrian is represented as a node in the network and the influence that each pedestrian has on the others is represented as an edge (an edge directed from node i to node j means that pedestrian j is influenced by pedestrian i). The strength of this influence is captured by the edge weight $w_{i,j} \in [0, 1]$ representing the normalised percentage of time in which pedestrian i leads pedestrian j. The network were reconstructed repeatedly within 5 consecutive time windows in order to evaluate also the evolution of the interactions over time (Figure 5(f) and Figure 6(f)).

The topologies inferred were then refined by means of DPI techniques (data processing inequality) and by a further thresholding to remove false positive links between nodes, as suggested in[34]. Specifically: i) links whose weights $w_{i,j}$ are null were discarded from the reconstructed network, and ii) non-zero weights $w_{i,j}$ were checked among all triplets of connected nodes so that, on the basis of their intensity, one of the triplet can be possibly regarded as a false connection and set to zero (so that the corresponding link was removed). For example, let us consider three nodes i, j and k. If the weight $w_{i,k}$ between the nodes i and k was lower than $w_{i,j}$ between the nodes i and j, and was also lower than $w_{j,k}$ between the nodes j and k, then the weight $w_{i,k}$ was set to zero and the link between the two nodes i and k was removed.
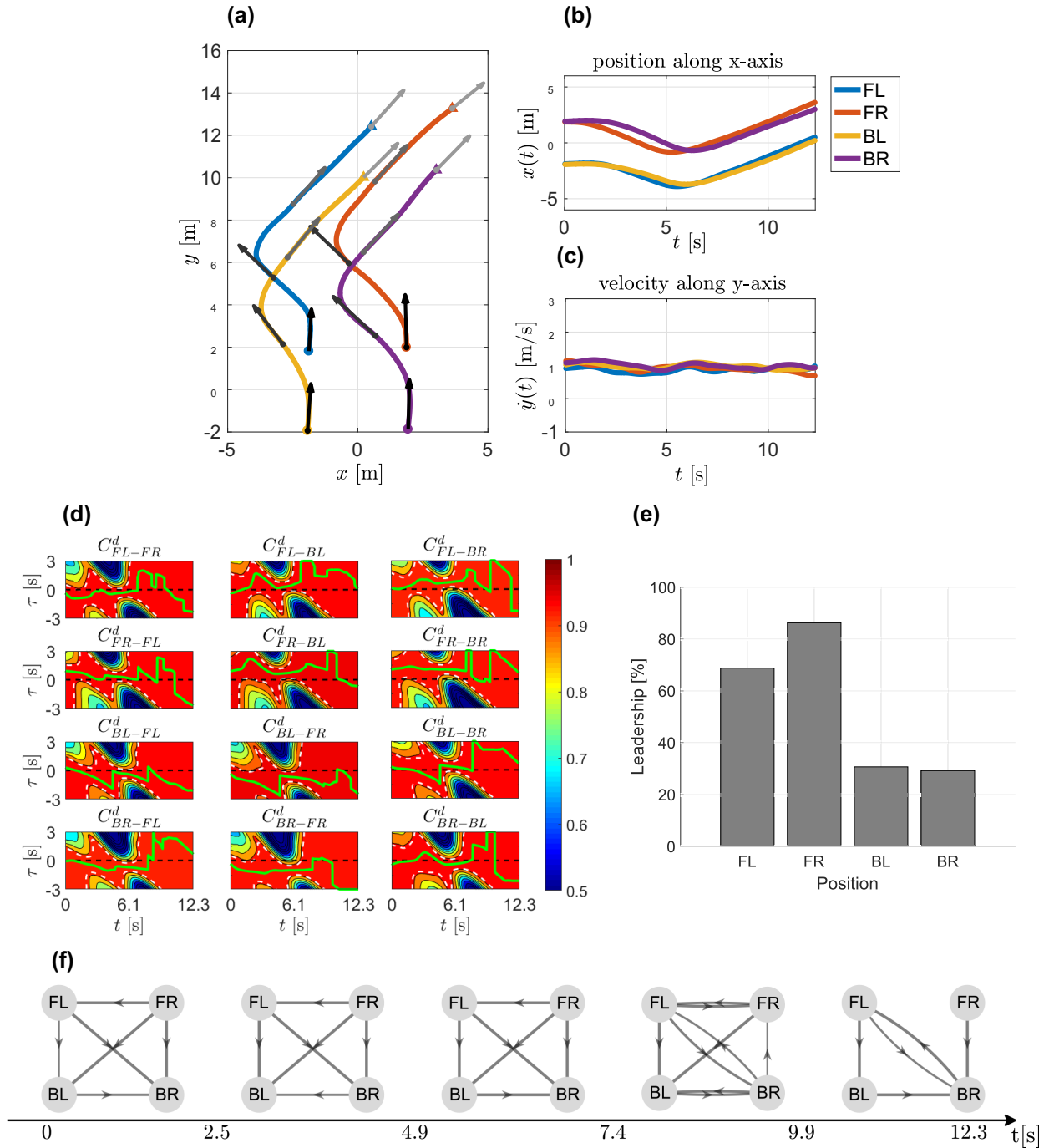
Figure 5. Left-right representative trial. (a) Pedestrians' trajectories in the *xy*-plane with different colours. Velocity vectors are represented by an arrow each 3 seconds, the colour goes from black to grey as time increases.(b-c) Position along *x*-axis and velocity along *y*-axis. Pedestrians are identified by his/her position (FL, FR, BL, BR). (d) TDDC evaluated for each pair of pedestrians. The *x*-axis represents time instant t, whereas the *y*-axis represents different values of the time-delay τ. Different colours are different values of TDDC, with blue representing $C_{ij}^d(t, \tau) \leq 0.5$ and red representing $C_{ij}^d(t, \tau) = 1$. Dashed white lines represent level curves where $C_{ij}^d(t, \tau) = 0.95$, whereas the dashed black line represents $\tau(t) = 0$. The solid green line on top of the heat map represents the value of $\tau(t)$ maximising the heading direction correlation between two pedestrians. (e) Percent leadership. Each grey bar refers to a different member in the group. (f) Network reconstruction. Each node represents a pedestrian, whereas the arrow directed from node i to node j indicates the fact that the heading direction of pedestrian i influences that of pedestrian j. The arrow's width is the strength of such interaction.
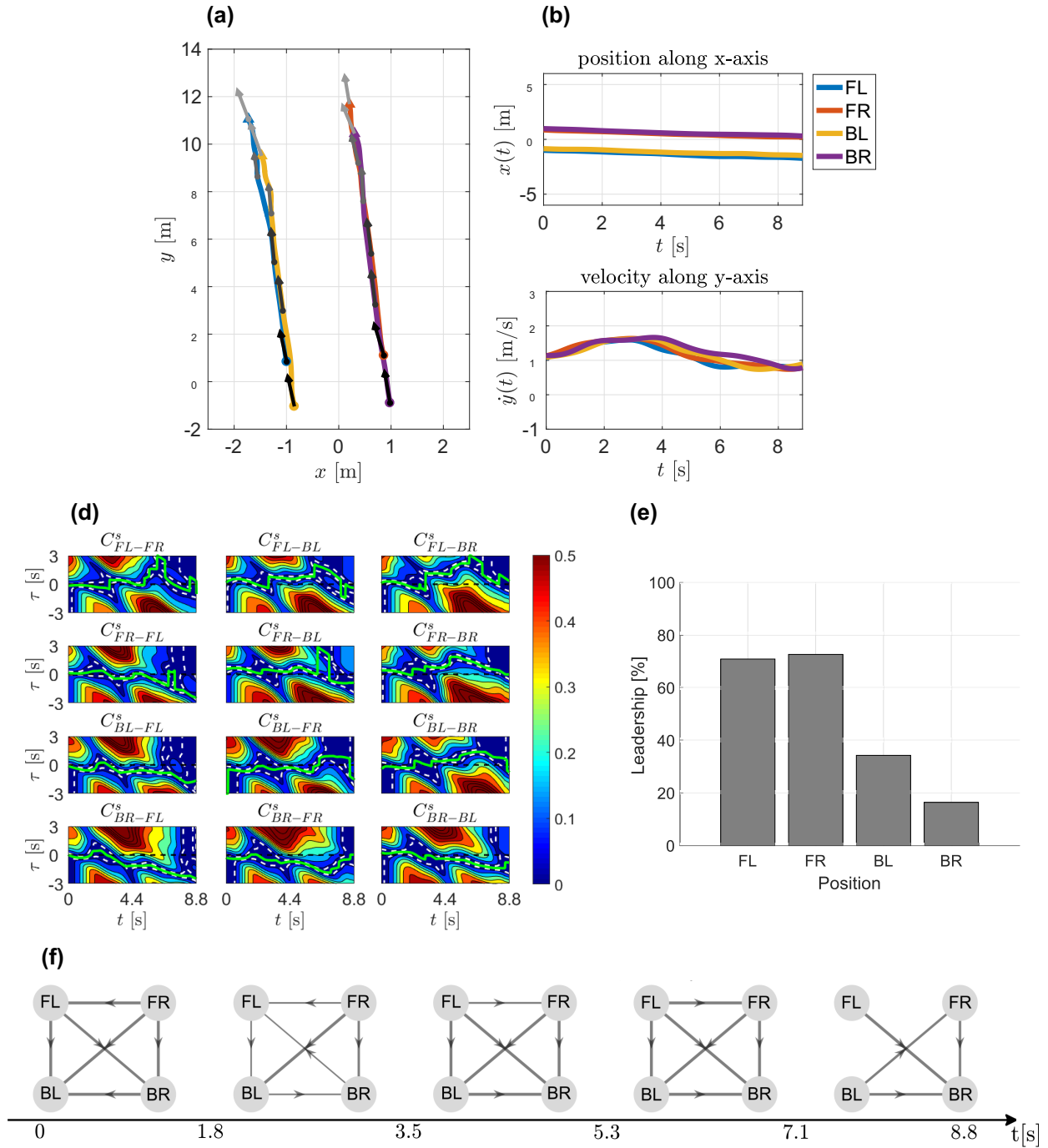
Figure 6. Fast-slow representative trial. (a) Pedestrians' trajectories in the *xy*-plane with different colours. Velocity vectors are represented by an arrow each 3 seconds, the colour goes from black to grey as time increases. (b-c) Position along *x*-axis and velocity along *y*-axis. Pedestrians are identified by his/her position (FL, FR, BL, BR). (d) TDSC evaluated for each pair of pedestrians. The *x*-axis represents time instant t, whereas the *y*-axis represents different values of the time-delay τ. Different colours are different values of TDSC, with blue representing $C_{ij}^s(t,\tau) = 0$ and red representing $C_{ij}^s(t,\tau) \geq 0.5$. Dashed white lines represent level curves where $C_{ij}^s(t,\tau) = 0.05$, whereas the dashed black line represents $\tau(t) = 0$. The solid green line on top of the heat map represents the value of $\tau(t)$ minimising the speed correlation between two pedestrians. (e) Percent leadership. Each grey bar refers to a different member in the group. (f) Network reconstruction. Each node represents a pedestrian, whereas the arrow directed from node i to node j indicates the fact that the speed of pedestrian i influences that of pedestrian j. The arrow's width is the strength of such interaction.

References

1. Abdallah, C. T. & Tanner, H. G. Complex networked control systems: Introduction to the special section. *IEEE Control. Syst. Mag.* **27**, 30–32 (2007).

2. Bullo, F. *Lectures on Network Systems* (2019), 1.3 edn. With contributions by J. Cortes, F. Dorfler, and S. Martinez.

3. Reebs, S. G. Can a minority of informed leaders determine the foraging movements of a fish shoal? *Animal Behav.* **59**, 403–409 (2000).

4. Couzin, I. D., Krause, J., Franks, N. R. & Levin, S. A. Effective leadership and decision-making in animal groups on the move. *Nature* **433**, 513–516 (2005).

5. Zienkiewicz, A., Barton, D. A., Porfiri, M. & Di Bernardo, M. Leadership emergence in a data-driven model of zebrafish shoals with speed modulation. *The Eur. Phys. Journal: Special Top.* **224**, 3343–3360 (2015).

6. Nagy, M., Ákos, Z., Biro, D. & Vicsek, T. Hierarchical group dynamics in pigeon flocks. *Nature* **464**, 890–893 (2010).

7. Orange, N. & Abaid, N. A transfer entropy analysis of leader-follower interactions in flying bats. *The Eur. Phys. J. Special Top.* **224**, 3279–3293 (2015).

8. Hooper, Paul L and Kaplan, Hillard S and Boone, James L. A theory of leadership in human cooperative groups. *J. Theor. Biol.* **265**, 633–646 (2010).

9. Von Rueden, Christopher and Gurven, Michael and Kaplan, Hillard and Stieglitz, Jonathan. Leadership in an egalitarian society. *Hum. Nat.* **25**, 538–566 (2014).

10. Gillet, Joris and Cartwright, Edward and Van Vugt, Mark. Selfish or servant leadership? Evolutionary predictions on leadership personalities in coordination games. *Pers. Individ. Differ.* **51**, 231–236 (2011).

11. Lukaszewski, Aaron W and Simmons, Zachary L and Anderson, Cameron and Roney, James R. The role of physical formidability in human social status allocation. *J. Pers. Soc. Psychol.* **110**, 385 (2016).

12. Bartling, Björn and Fehr, Ernst and Herz, Holger. The intrinsic value of decision rights. *Econometrica* **82**, 2005–2039 (2014).

13. Fehr, Ernst and Herz, Holger and Wilkening, Tom. The lure of authority: Motivation and incentive effects of power. *Am. Econ. Rev.* **103**, 1325–59 (2013).

14. Edelson, Micah G and Polania, Rafael and Ruff, Christian C and Fehr, Ernst and Hare, Todd A. Computational and neurobiological foundations of leadership decisions. *Science* **361** (2018).

15. D'Ausilio, A. *et al.* Leadership in orchestra emerges from the causal relationships of movement kinematics. *PLoS ONE* **7**, e35757 (2012).

16. Glowinski, D. *et al.* Multi-scale entropy analysis of dominance in social creative activities. In *ACM international conference on Multimedia*, 1035–1038 (2010).

17. Özcimder, K., Dey, B., Lazier, R. J., Trueman, D. & Leonard, N. E. Investigating group behavior in dance: an evolutionary dynamics approach. In *American Control Conference*, 6465–6470 (2016).

18. Leonard, N. E. *et al.* In the dance studio: An art and engineering exploration of human flocking. In *Controls and Art*, 27–49 (Springer, 2014).

19. Boos, M., Pritz, J., Lange, S. & Belz, M. Leadership in moving human groups. *PLoS Comput. Biol.* **10**, e1003541 (2014).

20. Dyer, J. R. *et al.* Consensus decision making in human crowds. *Animal Behav.* **75**, 461–470 (2008).

21. Dyer, J. R., Johansson, A., Helbing, D., Couzin, I. D. & Krause, J. Leadership, consensus decision making and collective behaviour in humans. *Philos. Transactions Royal Soc. B: Biol. Sci.* **364**, 781–789 (2009).

22. Alderisio, Francesco and Lombardi, Maria and di Bernardo, Mario. Emergence of leadership in complex networks and human groups. In *2018 IEEE International Symposium on Circuits and Systems (ISCAS)*, 1–5 (IEEE, 2018).

23. Gavrilets, Sergey and Auerbach, Jeremy and Van Vugt, Mark. Convergence to consensus in heterogeneous groups and the emergence of informal leadership. *Sci. reports* **6**, 1–10 (2016).

24. Rio, K. W., Dachner, G. C. & Warren, W. H. Local interactions underlying collective motion in human crowds. *Proc. Royal Soc. B: Biol. Sci.* **285**, 20180611 (2018).

25. Rio, K. & Warren, W. H. The visual coupling between neighbors in real and virtual crowds. *Transp. Res. Procedia* **2**, 132–140 (2014).

26. Rio, K. W., Rhea, C. K. & Warren, W. H. Follow the leader: Visual control of speed in pedestrian following. *J. Vis.* **14** (2014).

27. Faria, Jolyon J and Dyer, John RG and Tosh, Colin R and Krause, Jens. Leadership and social information use in human crowds. *Animal Behav.* **79**, 895–901 (2010).

28. Pelechano, N. & Badler, N. Modeling Crowd and Trained Leader Behavior during Building Evacuation. *IEEE Comput. Graph. Appl.* **6**, 80–86 (2006).

29. Challenger, R and Clegg, CW and Robinson, MA and Leigh, M. Understanding crowd behaviours. *Support. Theory Evid.* **2** (2009).

30. Stogdill, R. M. Personal factors associated with leadership: A survey of the literature. *The J. psychology* **25**, 35–71 (1948).

31. King, A. J., Johnson, D. D. & Van Vugt, M. The Origins and Evolution of Leadership. *Curr. Biol.* **19**, 911–916 (2009).

32. Dachner, G. C. & Warren, W. H. Behavioral dynamics of heading alignment in pedestrian following. *Transp. Res. Procedia* **2**, 69–76 (2014).

33. Giuggioli, L., McKetterick, T. J. & Holderied, M. Delayed response and biosonar perception explain movement coordination in trawling bats. *PLoS computational biology* **11**, e1004089 (2015).

34. Alderisio, F., Fiore, G. & di Bernardo, M. Reconstructing the structure of directed and weighted networks of nonlinear oscillators. *Phys. Rev. E* **95**, e042302 (2017).

Acknowledgements

Author contributions statement

Conceived and designed the experiments: W.H.W. Performed the experiments and collected the data: W.H.W. Metrics definition and performed the data analysis: M.L., M.d.B. Wrote the paper: M.L., M.d.B., W.H.W. All authors gave final approval for publication.

Additional information

Supplementary information accompanies this paper; **Competing Interests**: The authors declare that they have no competing interests.

Nonverbal leadership emergence in walking groups
- Supplementary Information -

Maria Lombardi[1,2], William H. Warren[3], Mario di Bernardo[1,2]

[1] Department of Engineering Mathematics, University of Bristol, Bristol, UK

[2] Department of Electrical Engineering and Information Technology, University of Naples Federico II, Naples, Italy

[3] Department of Cognitive, Linguistic and Psychological Sciences, Brown University, Providence, RI 02912, USA

Contents

Supplementary tables

1   Details about each trial are reported in Table 1 and 2 respectively for Group 1 and Group 2. A total of

2   3 trials out of 54 were discarded in the preprocessing analysis for data acquisition issues.

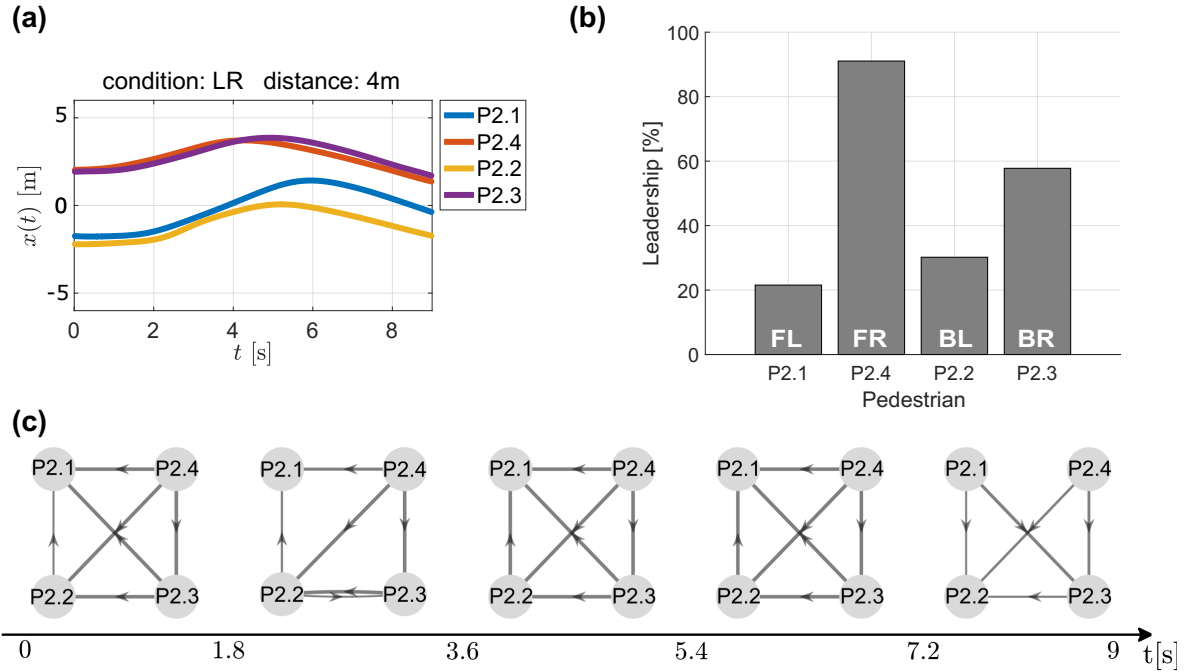| Trial	Condition	IPD [m]	Group	Pedestrian [FL, FR, BL, BR]
1	direction (left, left)	4	1	[P1.1, P1.4, P1.2, P1.3]
2	direction (left, right)	2	1	[P1.2, P1.3, P1.1, P1.4]
3	direction (left, right)	4	1	[P1.4, P1.1, P1.3, P1.2]
4	direction (right, left)	2	1	[P1.1, P1.2, P1.4, P1.3]
5	direction (left, left)	2	1	[P1.3, P1.4, P1.2, P1.1]
6	direction (right, right)	1	1	[P1.4, P1.2, P1.3, P1.1]
7	direction (right, right)	2	1	[P1.1, P1.2, P1.3, P1.4]
8	direction (left, left)	1	1	[P1.1, P1.4, P1.3, P1.2]
9	direction (right, left)	4	1	[P1.2, P1.3, P1.4, P1.1]
10	direction (right, right)	4	1	[P1.1, P1.4, P1.3, P1.2]
11	direction (right, left)	1	1	[P1.4, P1.1, P1.3, P1.2]
12	control	2	1	[P1.2, P1.3, P1.4, P1.1]
13	control	4	1	[P1.3, P1.1, P1.4, P1.2]
14	speed (fast, slow)	2	1	[P1.4, P1.2, P1.1, P1.3]
15	speed (slow, slow)	2	1	[P1.3, P1.2, P1.1, P1.4]
16	control	1	1	[P1.1, P1.4, P1.3, P1.2]
17	speed (slow, fast)	1	1	[P1.1, P1.3, P1.2, P1.4]
18	speed (fast, slow)	4	1	[P1.2, P1.4, P1.3, P1.1]
19	speed (fast, fast)	4	1	[P1.3, P1.2, P1.4, P1.1]
20	speed (slow, slow)	1	1	[P1.1, P1.2, P1.3, P1.4]
21	speed (fast, fast)	2	1	[P1.4, P1.3, P1.2, P1.1]
22	speed (slow, fast)	1	1	[P1.2, P1.4, P1.1, P1.3]
23	speed (fast, fast)	1	1	[P1.1, P1.3, P1.4, P1.2]
24	speed (slow, slow)	4	1	[P1.4, P1.1, P1.3, P1.2]
25	speed (fast, slow)	1	1	[P1.2, P1.1, P1.3, P1.4]
26	speed (slow, fast)	2	1	[P1.4, P1.3, P1.2, P1.1]

Supplementary Table 1: Details about the trials carried out by Group 1. Trial condition, initial inter-personal distance (IPD) between participants, and participants' positions are specified.

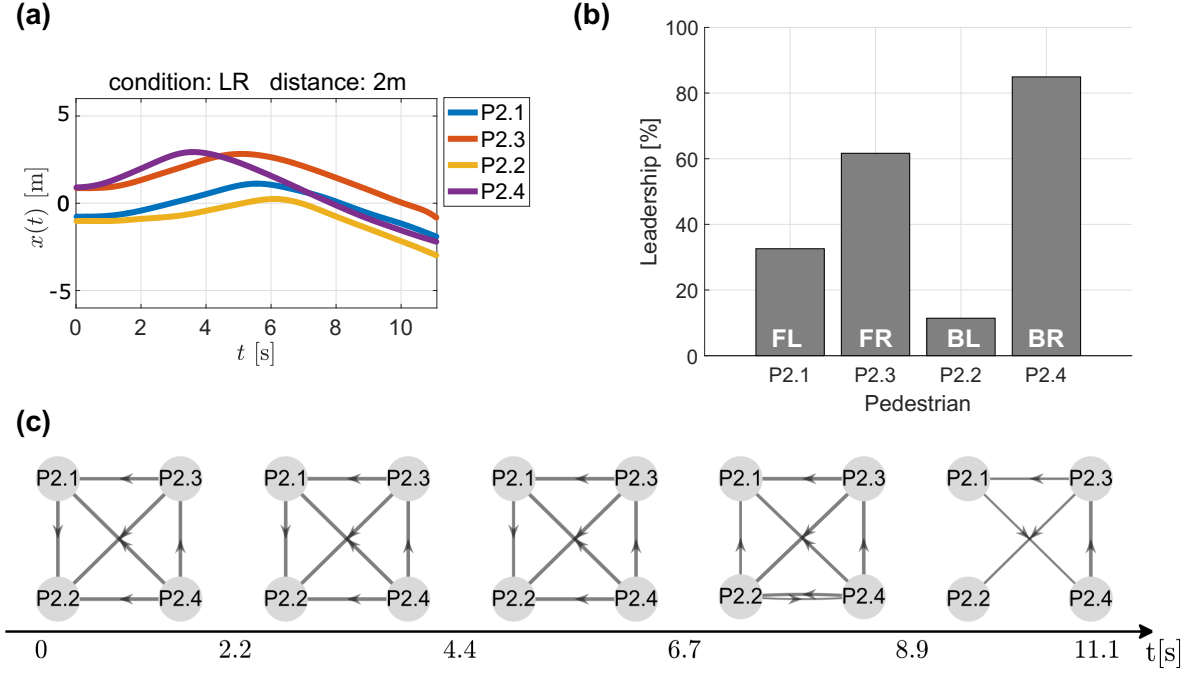| Trial	Condition	IPD [m]	Group	Pedestrian [FL, FR, BL, BR]
1	control	2	2	[P2.4, P2.2, P2.1, P2.3]
2	speed (fast, slow)	4	2	[P2.1, P2.2, P2.4, P2.3]
3	speed (slow, slow)	1	2	[P2.2, P2.1, P2.4, P2.3]
4	speed (slow, fast)	2	2	[P2.1, P2.3, P2.2, P2.4]
5	speed (slow, fast)	4	2	[P2.2, P2.4, P2.1, P2.3]
6	speed (fast, slow)	1	2	[P2.1, P2.3, P2.4, P2.2]
7	control	1	2	[P2.4, P2.1, P2.2, P2.3]
8	speed (slow, fast)	1	2	[P2.2, P2.4, P2.1, P2.3]
9	speed (fast, fast)	2	2	[P2.3, P2.4, P2.2, P2.1]
10	speed (fast, fast)	1	2	[P2.3, P2.1, P2.4, P2.2]
11	speed (slow, slow)	4	2	[P2.4, P2.2, P2.3, P2.1]
12	speed (fast, fast)	4	2	[P2.1, P2.4, P2.2, P2.3]
13	speed (slow, slow)	2	2	[P2.2, P2.1, P2.4, P2.3]
14	control	4	2	[P2.4, P2.2, P2.1, P2.3]
15	speed (fast, slow)	2	2	[P2.2, P2.4, P2.1, P2.3]
16	direction (left, right)	4	2	[P2.1, P2.4, P2.2, P2.3]
17	direction (left, right)	2	2	[P2.1, P2.3, P2.2, P2.4]
18	direction (right, right)	4	2	[P2.1, P2.4, P2.3, P2.2]
19	direction (left, left)	4	2	[P2.2, P2.1, P2.4, P2.3]
20	direction (left, left)	1	2	[P2.4, P2.3, P2.1, P2.2]
21	direction (left, right)	1	2	[P2.3, P2.2, P2.1, P2.4]
22	direction (right, left)	4	2	[P2.3, P2.2, P2.1, P2.4]
23	direction (right, left)	2	2	[P2.2, P2.3, P2.4, P2.1]
24	direction (left, left)	2	2	[P2.1, P2.4, P2.2, P2.3]
25	direction (right, right)	1	2	[P2.1, P2.2, P2.4, P2.3]

Supplementary Table 2: Details about the trials carried out by Group 2. Trial condition, initial inter-personal distance (IPD) between participants, and participants' positions are specified.
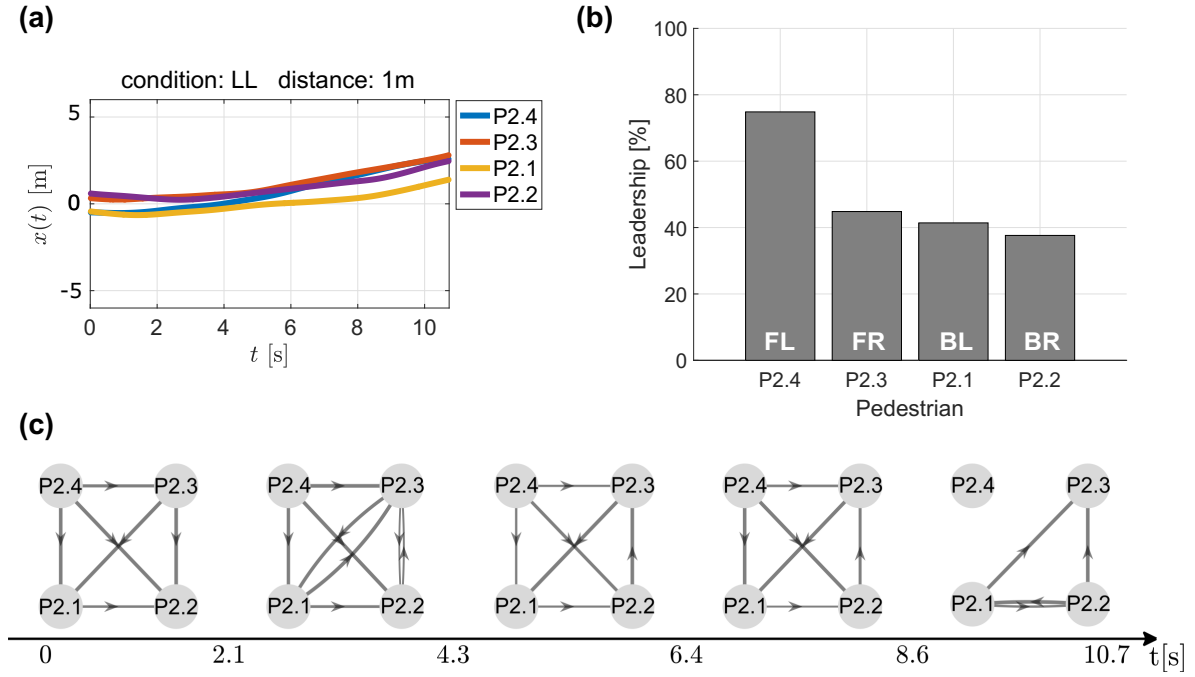
Supplementary figures

In order to confirm our findings in the main text, in this section we show further evidence that participant P2.4 effectively assumes leadership role independent of his/her position in the group. In Figure 1, 2, 3, 4 four sample trials are visualised, where the participant is respectively on the front right, back right, front left and back left position. It is clear that participant P2.4 moves first in all conditions, acting as leader even if he/she is located in the back positions of the group. Furthermore, in the network reconstruction the same participant has only outgoing edges meaning that the participant under investigation influences the others but is seldom influenced.
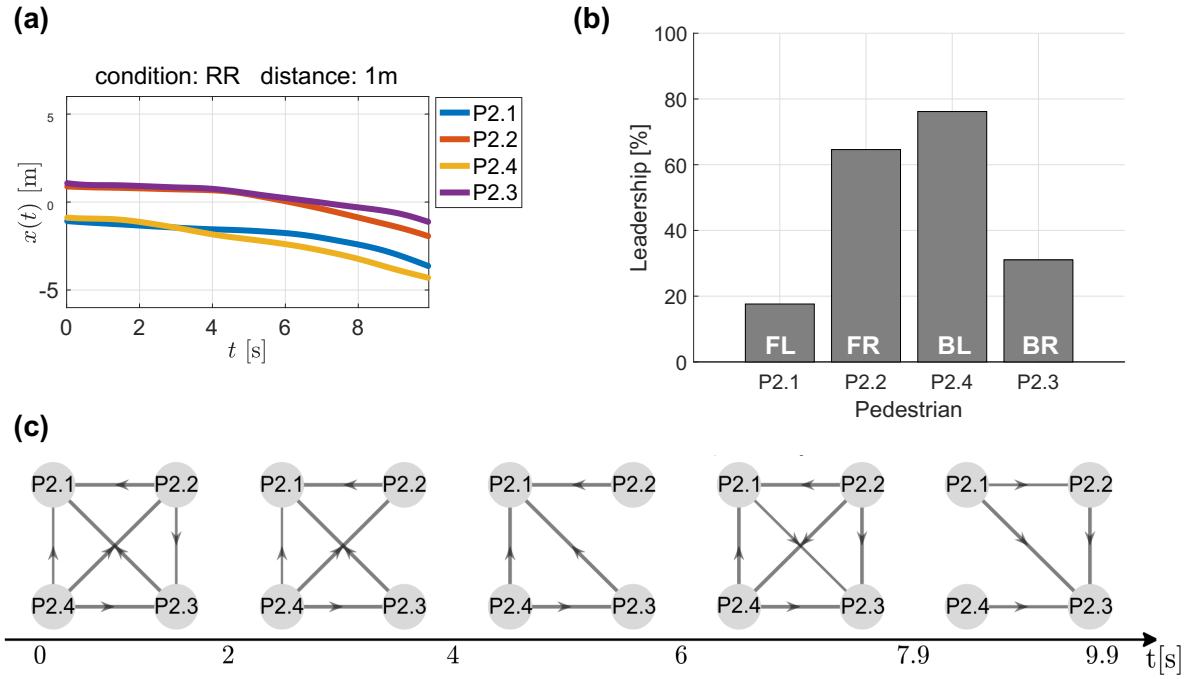
(a) condition: LR   distance: 4m

(b)

(c)

Supplementary Figure 1: **Participant P**2.4 **in the front right position.** Direction-change trial implementing the sequence "LR" (turn left, turn right) and having an initial distance between participants of 4 metres. *(a) Velocity time series.* Pedestrians' velocity time series in the *xy*-plane where the *x*-axis represents the time in seconds and the *y*-axis the horizontal component of the velocity vector. Different pedestrians are characterised by different colours and identified by the label P*x.y*, where *x* is the group and *y* is the specific member of the group. *(b) Percent leadership.* Each grey bar represents the percentage of leadership taken by the participant in the group during the trial. The labels FL, FR, BL, BR on each bar refer to the position occupied by the corresponding pedestrians and they are "front left, front right, back left, back right". *(c) Network reconstruction.* Each node represents a participant. The interaction between them are graphically represented through an arrow with different width, the thicker the arrow the stronger the interaction. Five different networks are reconstructed over different time-windows.

Supplementary Figure 2: **Participant P**2.4 **in the back right position.** Direction-change trial implementing the sequence "LR" (turn left, turn right) and having an initial distance between participants of 2 metres. *(a) Velocity time series.* Pedestrians' velocity time series in the *xy*-plane where the *x*-axis represents the time in seconds and the *y*-axis the horizontal component of the velocity vector. Different pedestrians are characterised by different colours and identified by the label P*x.y*, where *x* is the group and *y* is the specific member of the group. *(b) Percent leadership.* Each grey bar represents the percentage of leadership taken by the participant in the group during the trial. The labels FL, FR, BL, BR on each bar refer to the position occupied by the corresponding pedestrians and they are "front left, front right, back left, back right". *(c) Network reconstruction.* Each node represents a participant. The interaction between them are graphically represented through an arrow with different width, the thicker the arrow the stronger the interaction. Five different networks are reconstructed over different time-windows.

Supplementary Figure 3: **Participant P**2.4 **in the front left position.** Direction-change trial implementing the sequence "LL" (turn left, turn left) and having an initial distance between participants of 1 metre. *(a) Velocity time series.* Pedestrians' velocity time series in the *xy*-plane where the *x*-axis represents the time in seconds and the *y*-axis the horizontal component of the velocity vector. Different pedestrians are characterised by different colours and identified by the label P*x.y*, where *x* is the group and *y* is the specific member of the group. *(b) Percent leadership.* Each grey bar represents the percentage of leadership taken by the participant in the group during the trial. The labels FL, FR, BL, BR on each bar refer to the position occupied by the corresponding pedestrians and they are "front left, front right, back left, back right". *(c) Network reconstruction.* Each node represents a participant. The interaction between them are graphically represented through an arrow with different width, the thicker the arrow the stronger the interaction. Five different networks are reconstructed over different time-windows.

(a)

condition: RR   distance: 1m

(b)

(c)

Supplementary Figure 4: **Participant P**2.4 **in the back left position.** Direction-change trial implementing the sequence "RR" (turn right, turn right) and having an initial distance between participants of 1 metre. *(a) Velocity time series.* Pedestrians' velocity time series in the *xy*-plane where the *x*-axis represents the time in seconds and the *y*-axis the horizontal component of the velocity vector. Different pedestrians are characterised by different colours and identified by the label P*x.y*, where *x* is the group and *y* is the specific member of the group. *(b) Percent leadership.* Each grey bar represents the percentage of leadership taken by the participant in the group during the trial. The labels FL, FR, BL, BR on each bar refer to the position occupied by the corresponding pedestrians and they are "front left, front right, back left, back right". *(c) Network reconstruction.* Each node represents a participant. The interaction between them are graphically represented through an arrow with different width, the thicker the arrow the stronger the interaction. Five different networks are reconstructed over different time-windows.