Reconstruction of Leadership Interaction Networks in Walking Crowds

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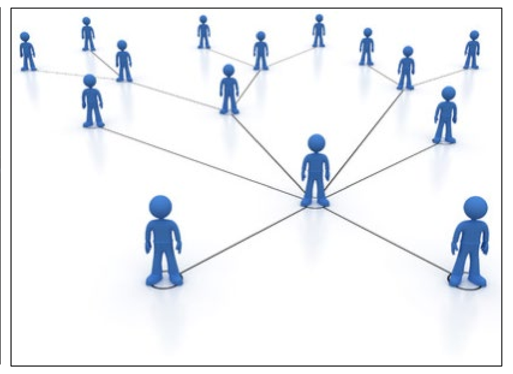
Poster 43.354
Vision Sciences Society, May 16, 2022
Supported by NSF BCS-1849446

The Problem

Human 'flocking' is a self-organized behavior that emerges from visual interactions between pedestrians [1]. Leadership plays a pivotal role in such collective crowd motion, especially when initiating and modulating group behaviors [2]. But the mechanism of 'leadership' – how individual pedestrians influence a group – has not been established.

Here we explore the reconstruction and analysis of visual interaction networks in human crowds.

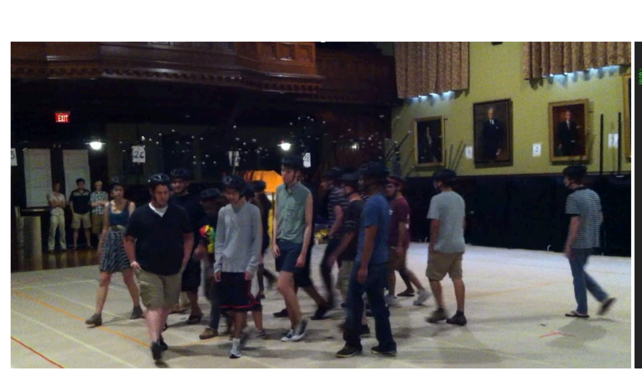
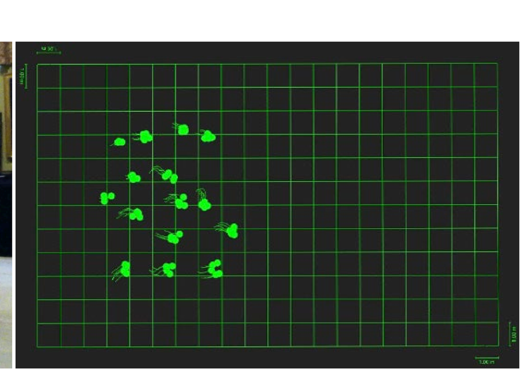
Goals

- Reconstruct visual networks
- Determine whether leadership is a quality of individuals or emerges from crowd dynamics
- Identify influential positions within a crowd
- Control a crowd by manipulating covert leaders

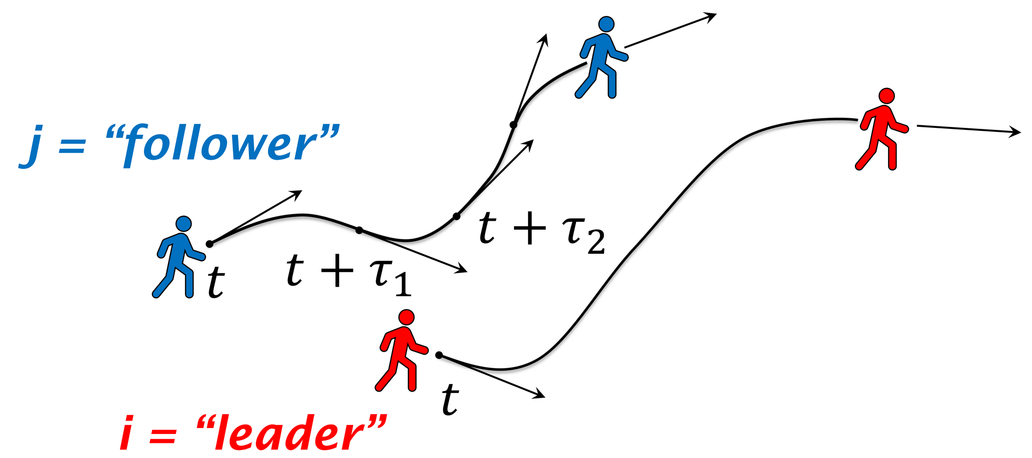
Experiment

Method

- 12 trials (10, 16, 20 participants; 4 trials each)
- Veer randomly, stay together
- 2 minutes each
- Movements recorded with helmets with markers

Time-Dependent Delayed Correlation (TDDC) [3]



Indicator of heading alignment:

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

Indicator of leadership:

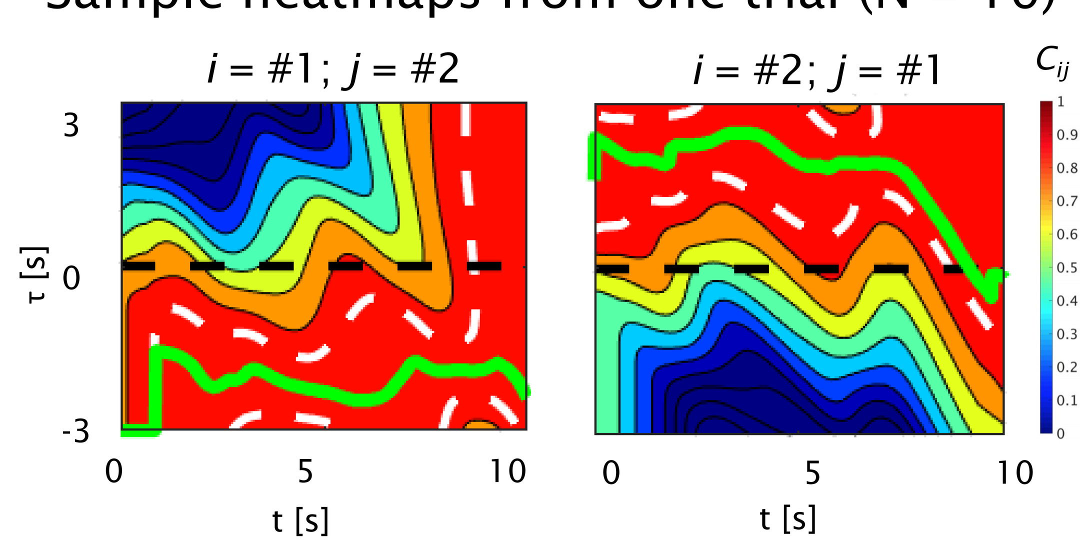
$$C_{ij}^{d}(t,\tau) = \frac{1}{2\omega+1} \sum_{k=-\omega}^{\omega} h_{ij}(t+k\Delta t, \tau)$$

- Correlation in heading direction at different time delays

  →Mean of $h_{ij}(t,\tau)$ over a symmetric time window $2\omega\Delta t$

TDDC Heatmap

Sample heatmaps from one trial (N = 16)



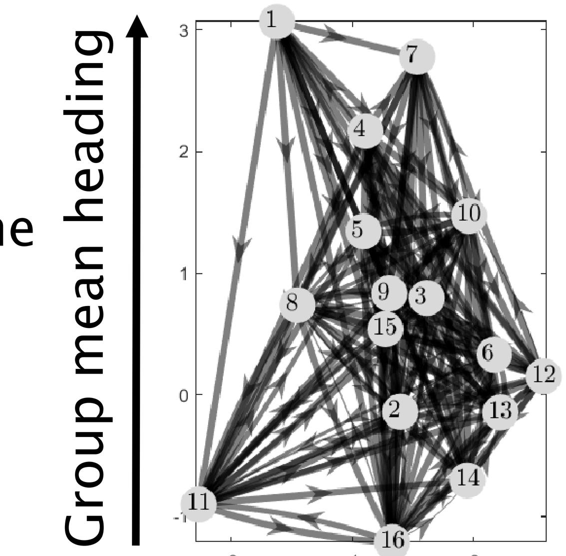
i is leading *j* when max C_{ij} — is positive

t = time point in the trial
τ = time delay with respect to t
— = time delay τ_{ij} maximizing the correlation in heading direction between agents *i* and *j* at time *t*

Network Reconstruction

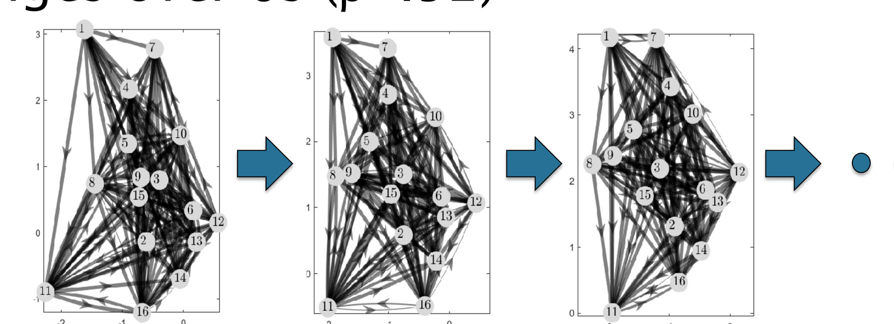
Network Structure

- Influence = % of time *i* leads *j*
  - Weight = thickness of the link
  - Computed for every possible link



Network Dynamics

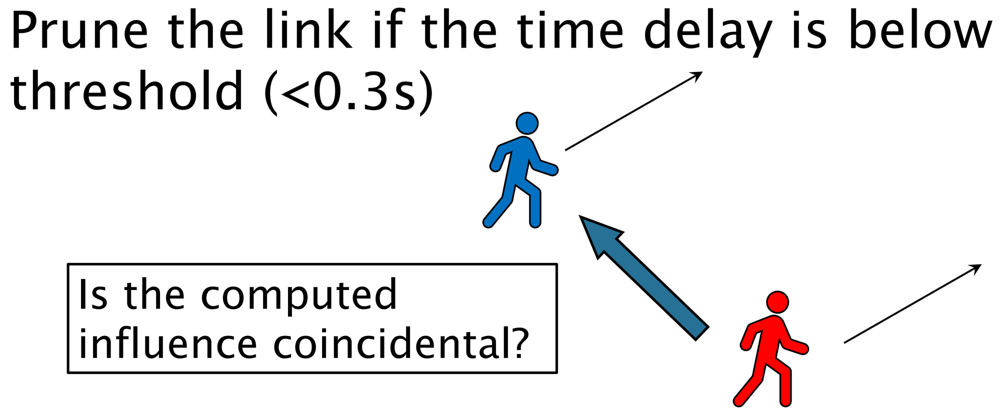
- Reconstruct network in successive time intervals
- Leadership ranking is stable for 1s (ρ=.86), but changes over 6s (ρ=.52)



Pruning the Network

1. Time delay

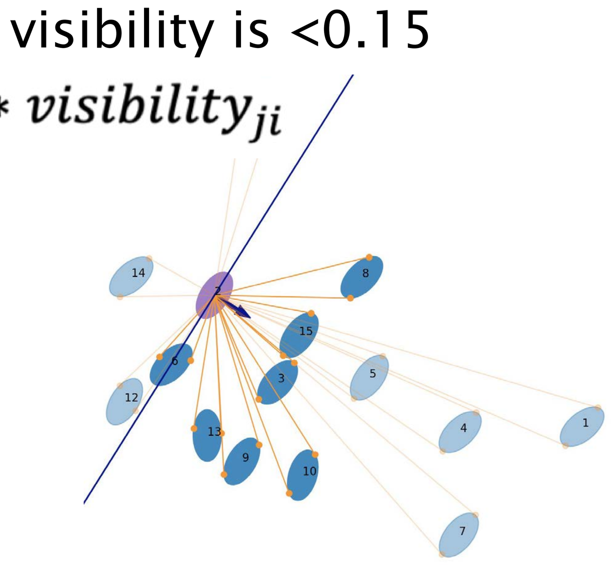
- Compute mean time delay in a 1s interval
- Prune the link if the time delay is below the threshold (<0.3s)



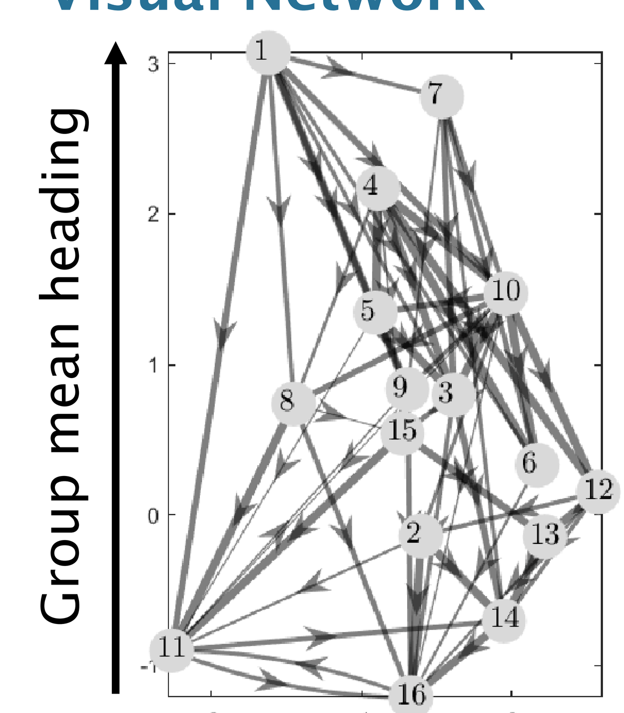
2. Visual connections (field of view & occlusion)

- Weight each link by neighbor visibility in a 1s interval
- Prune the link if mean visibility is <0.15

$$w_{new\_ij} = w_{original\_ij} * visibility_{ji}$$

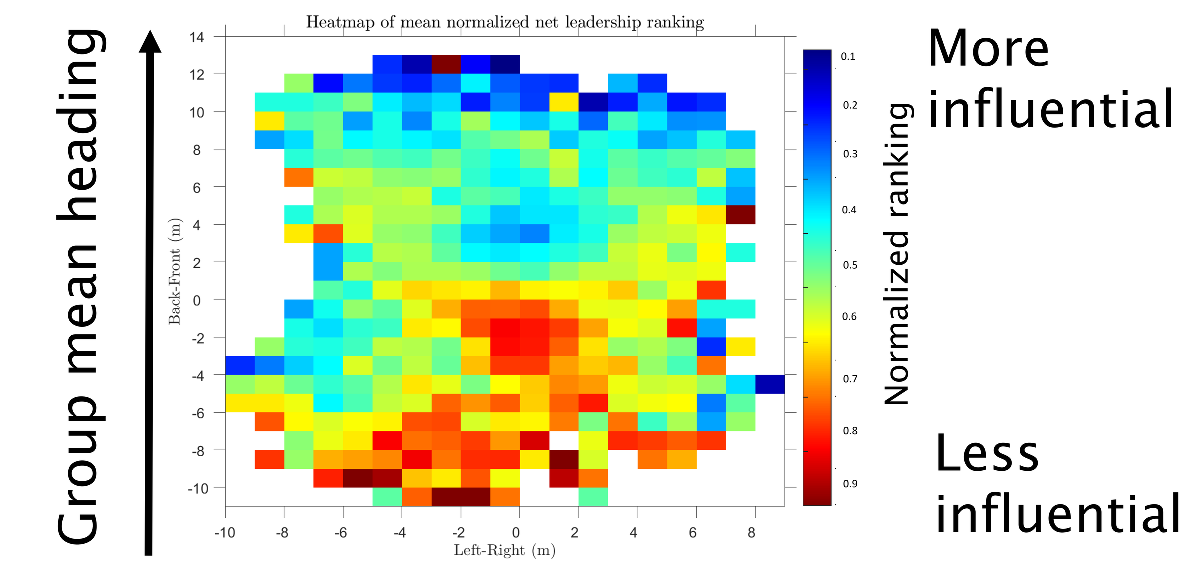


Visual Network



After pruning, 46% of links were deleted or adjusted compared to the original network

Spatial Analysis of Leadership Positions

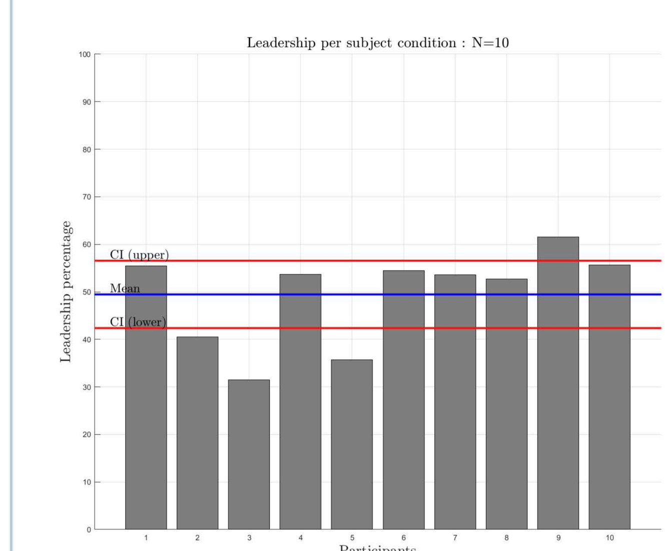


Mean net leadership ranking (normalized) (total outdegree – total indegree)

→Leadership strongly depends on spatial position

- Front positions are most influential (blue)
- Rear and central positions tend to follow (red)

Individual Leadership Index [2]



Percentage of time each subject acts as a leader across trials

- 1 above, 3 below the 95% CI

  M=49.24; SD=9.10; 95% CI [44.39, 54.90]

→Leadership modestly depends on individual qualities

Conclusions

- Visual interaction networks can be reliably reconstructed
- Leadership is largely emergent
  - changes dynamically in 6s
  - strongly depends on spatial position
  - confederates in key positions might steer or split crowd
- Also moderately depends on individual qualities

References

1. Dachner, G. C., Wirth, T. D., Richmond, E., & Warren, W. H. (2022). *Proc Royal Society B, 289*(1970), 20212089. https://royalsocietypublishing.org/doi/10.1098/rspb.2021.2089
2. Lombardi, M., Warren, W. H., & di Bernardo, M. (2020). *Scientific Reports, 10*(1), 18948. https://doi.org/10.1038/s41598-020-75551-2
3. Giuggioli, L., McKetterick, T. J., & Holderied, M. (2015). *PLOS Computational Biology, 11*(3), e1004089. https://doi.org/10.1371/journal.pcbi.1004089