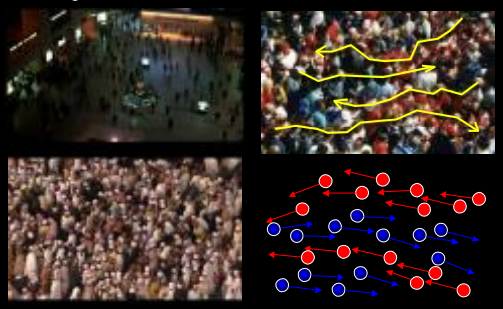
Collective motion in pedestrian crowds

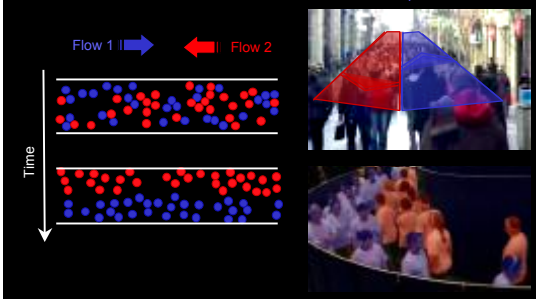
Self-organized lane formation



Homo sapiens

Collective motion in pedestrian crowds

Self-organized lane formation



Spatial organization of bidirectional pedestrian flows

Collective motion in pedestrian crowds

Asymmetric avoidance behavior

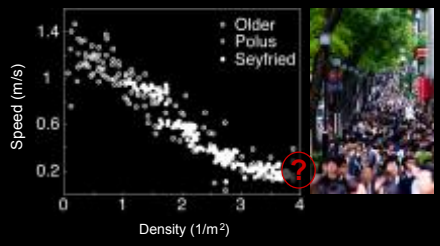
Right hand-side preference (France)

Left hand-side preference (Japan)

Helbing, D. *et al.*, *Environment and Planning B : Planning and Design* (2001)

Collective motion in pedestrian crowds

Fundamental diagram



Older, S.J., *Traffic Engineering and Control* (1968)
Polus A. *et al.*, *Journal of Transportation Engineering* (1983)
Seyfried A. *et al.*, *Journal of Statistical Mechanics* (2005)

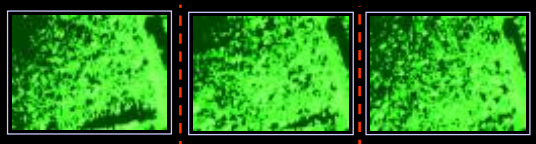
Collective motion in pedestrian crowds

High density conditions

Helbing, D. *et al.*, *Phys. Rev. E.*, (2007)

Collective motion in pedestrian crowds

Flow regime transitions in a moving crowd



Helbing, D. *et al.*, *Phys. Rev. E.*, (2007)

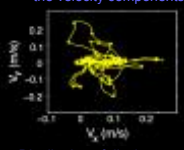
Collective motion in pedestrian crowds

Turbulent crowd dynamics leads to "crowd quakes"

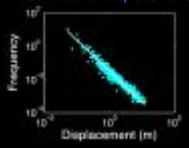
Turbulent flow

On 24 September 2015, a crowd collapse caused the deaths of at least 2,070 pilgrims during the annual Hajj pilgrimage in Mecca

Temporal evolution of the velocity components



Distribution of displacements



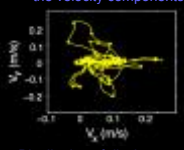
Helbing, D. *et al.*, *Phys. Rev. E.*, (2007)

Collective motion in pedestrian crowds

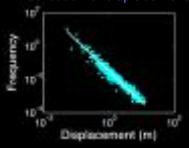
Turbulent crowd dynamics leads to "crowd quakes"

Loveparade, Duisbourg, Germany, July, 24, 2010 (21 people died)

Temporal evolution of the velocity components



Distribution of displacements



Helbing, D. *et al.*, *Phys. Rev. E.*, (2007)

Experimental study of collective motion in pedestrian crowds

Observations and measures at different scales

Individual level

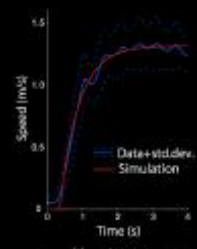
Collective level

Field observations

Experimental study of collective motion in pedestrian crowds

Controlled experiments: single pedestrian behavior

Single pedestrian behavior



$$\frac{d\vec{v}_i}{dt} = \frac{1}{\tau}(v_i^0 \vec{e}_i^0 - \vec{v}_i(t))$$

$\tau = 0.64 \pm 0.05$ s (relaxation time)

Moussaïd, M. *et al.*, *Proc. R. Soc. B*, (2009)

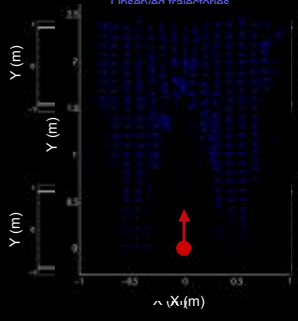
Experimental study of collective motion in pedestrian crowds

Controlled experiments: binary interactions

Interaction with a standing pedestrian

Interaction with a pedestrian moving in opposite direction

Average value of the interaction effect



Experimental study of collective motion in pedestrian crowds

Controlled experiments: collective dynamics and patterns

Experimental set-up

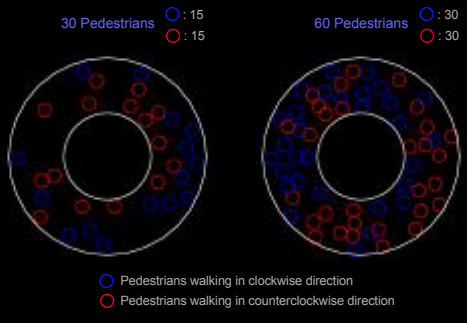
Experimental study of collective motion in pedestrian crowds

Controlled experiments: collective dynamics and patterns

- Groups of pedestrians moving in the same direction and in opposite direction have been tracked in the corridor during 1mn sessions
- The influence of pedestrians density on lanes formation was investigated in groups of increasing sizes (N = 10, 20, 20, 30, 40, 50, 60)
- Unidirectional and asymetric flows (75% clockwise direction/25% anti-clockwise direction)

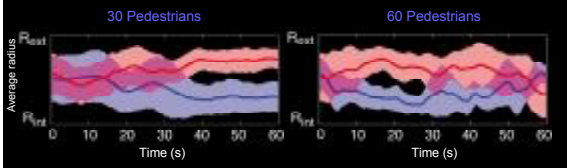
Experimental study of collective motion in pedestrian crowds

Lane formation in bidirectional traffic experiments



Experimental study of collective motion in pedestrian crowds

Segregation dynamics and traffic instabilities

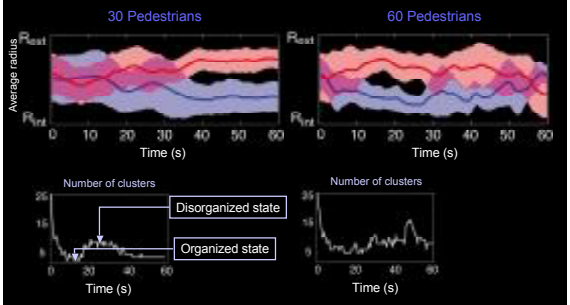


- There is an alternation of mixed and segregated phases

Moussaïd, M. *et al.*, *Plos Comp Biol*, (2012)

Experimental study of collective motion in pedestrian crowds

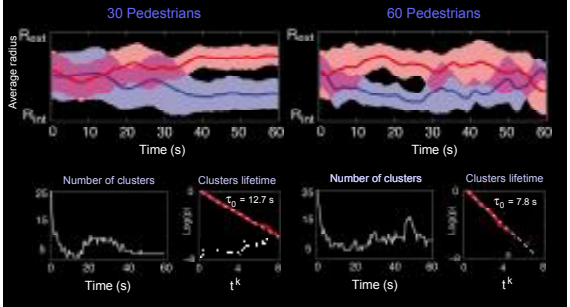
Segregation dynamics and traffic instabilities



Moussaïd, M. *et al.*, *Plos Comp Biol*, (2012)

Experimental study of collective motion in pedestrian crowds

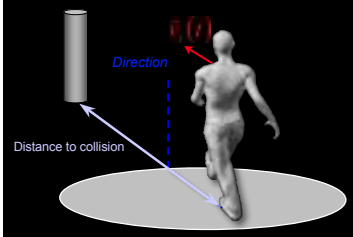
Segregation dynamics and traffic instabilities



Moussaïd, M. *et al.*, *Plos Comp Biol*, (2012)

Experimental study of collective motion in pedestrian crowds

Pedestrians behavioral rules

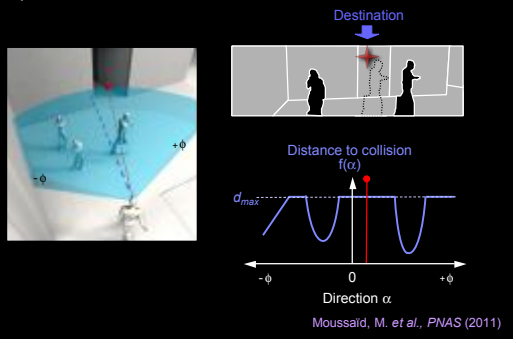


- Pedestrians are continuously adapting their walking speed and their direction of motion to avoid collisions
- What kind of information is used by pedestrians to adapt their walking behavior?
- Vision is the main source of information used by pedestrian to control their motion
- Pedestrians can estimate the time to collision with surrounding obstacles and can anticipate the motion of other pedestrians

Gibson, J.J., *Br. J. Psych.* (1958)

A model of pedestrian behavior based on behavioral heuristics

Representation of visual information



Moussaïd, M. *et al., PNAS* (2011)

A model of pedestrian behavior based on behavioral heuristics

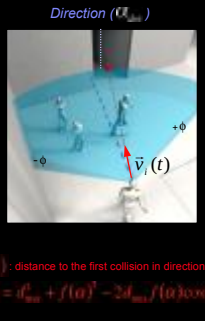
Fast and frugal heuristics

- In everyday life situations, people make decisions using simple behavioral heuristics (step-by-step rules) that function well under the constraints of limited search, knowledge, and time
- Pedestrians could use simple rules when they have to make a quick decision in complex environments

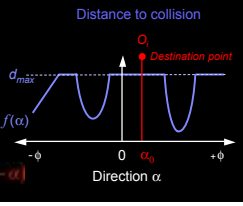
Gigerenzer, G. *et al.*, (1999)
Bonabeau, E., Dorigo, M. & Theraulaz, G., (1999)

A model of pedestrian behavior based on behavioral heuristics

First heuristic: hunting for gaps



- A pedestrian chooses the direction α_{des} that allows the most direct path to the destination point O_i, taking into account the presence of obstacles
- α_{des} is computed through the minimization of $d(\alpha)$



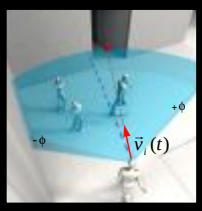
$f(\alpha)$: distance to the first collision in direction α

$d(\alpha) = d_{max}^2 + f(\alpha)^2 - 2d_{max} f(\alpha)\cos(\alpha_i - \alpha)$

A model of pedestrian behavior based on behavioral heuristics

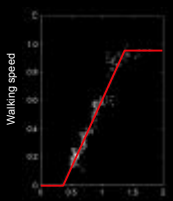
Second heuristic: maintain a safe distance to the nearest obstacle

- A pedestrian keeps a time to collision of time period τ with respect to the first obstacle in the chosen walking desired direction



Walking speed

$v_{des}(\tau) = \min\left[v_i, d_i/\tau\right]$



Adaptation of the walking speed

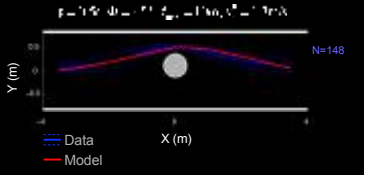
$\frac{d\vec{v}_i}{dt} = \frac{1}{\tau}(\vec{v}_{des} - \vec{v}_i)$

Seyfried, A. *et al., J. Stat. Mech.* (2005)

A model of pedestrian behavior based on behavioral heuristics

Model's predictions compared to experimental observations

Interaction with a standing pedestrian



Interaction with a pedestrian moving in opposite direction

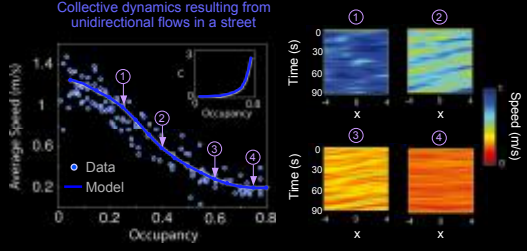
- The two simple behavioral heuristics implemented in the model are able to reproduce quantitatively realistic trajectories at the individual level

Moussaïd, M. *et al., PNAS* (2011)

A model of pedestrian behavior based on behavioral heuristics

Model's predictions compared to experimental observations

Collective dynamics resulting from unidirectional flows in a street



Street length: 8m
Street width: 3m

Moussaïd, M. *et al., PNAS* (2011)

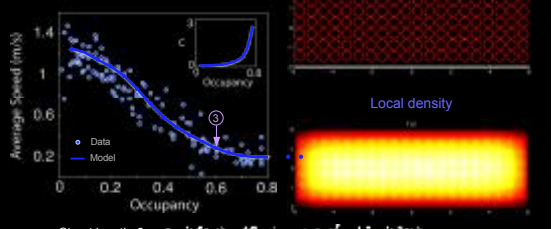
A model of pedestrian behavior based on behavioral heuristics

Model's predictions compared to experimental observations

Collective dynamics resulting from unidirectional flows in a street

Stop-and-go waves

Local density



Street length: 8m
Street width: 4m

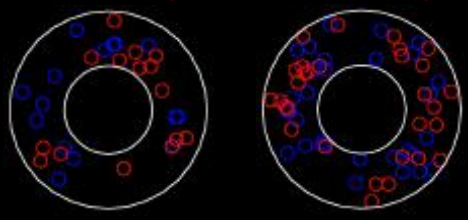
Moussaïd, M. *et al.*, *PNAS* (2011)

A model of pedestrian behavior based on behavioral heuristics

Simulations of bi-directional traffic

30 Pedestrians : 15 : 15

60 Pedestrians : 30 : 30



Pedestrians walking in clockwise direction

Pedestrians walking in counterclockwise direction

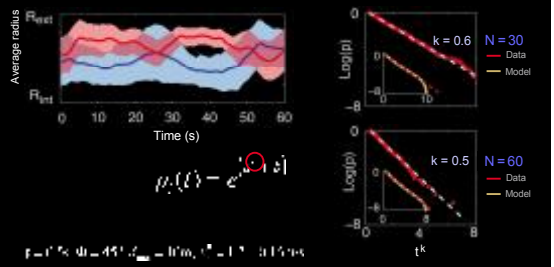
Moussaïd, M. *et al.*, *Plos Comp Biol*, (2012)

A model of pedestrian behavior based on behavioral heuristics

Model's predictions compared to experimental observations

Segregation dynamics

Clusters lifetime

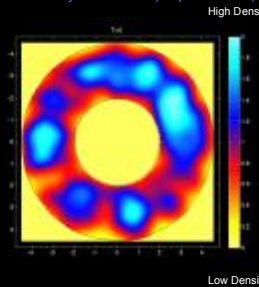


Moussaïd, M. *et al.*, *Plos Comp Biol*, (2012)

A model of pedestrian behavior based on behavioral heuristics

Correlation between local radial speed and density gaps

Density fluctuations (60 pedestrians)



- Data analysis reveals important density fluctuations in the experimental corridor

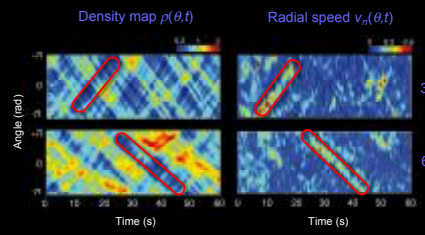
Moussaïd, M. *et al.*, *Plos Comp Biol*, (2012)

A model of pedestrian behavior based on behavioral heuristics

Correlation between local radial speed and density gaps

Density map $\rho(\theta,t)$

Radial speed $v_r(\theta,t)$



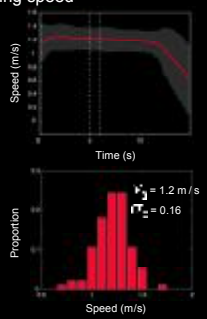
Moussaïd, M. *et al.*, *Plos Comp Biol*, (2012)

A model of pedestrian behavior based on behavioral heuristics

Variability of the comfortable walking speed

Tracking single pedestrian

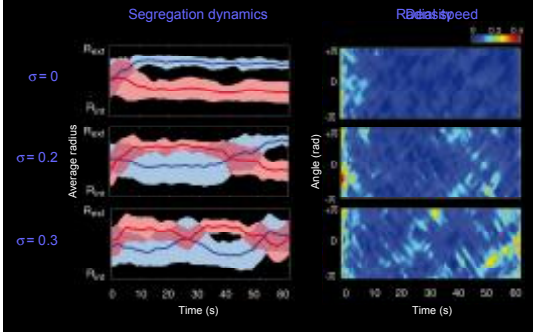
- Testing the effect of inter-individual variability of walking speed on traffic instability



Moussaïd, M. *et al.*, *Plos Comp Biol*, (2012)

A model of pedestrian behavior based on behavioral heuristics

Speed variability and traffic instabilities



A model of pedestrian behavior based on behavioral heuristics

High density conditions: the role of physical interactions

Experimental investigation of pushing behavior in a moving crowd

- In cases of overcrowding, physical interactions between bodies may occur, causing unintentional movements that are not determined by the behavioral heuristics
- The physical interaction with a pedestrian j is represented by:

$$f_{ij} = -k_1[r_i - d_{ij}]n_{ij}$$

- The resulting acceleration equation is:

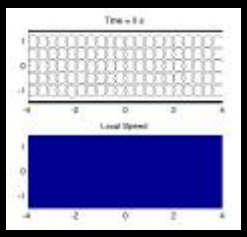
$$\frac{dv_i}{dt} = \frac{v_i^0 e_i^0 - v_i}{\tau} + \sum_{j \neq i} f_{ij} + \sum_{w} f_{iw}$$

Effects of body collisions | Physical interaction with walls

A model of pedestrian behavior based on behavioral heuristics

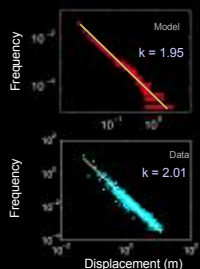
Model's predictions compared to observations

Crowd turbulence



Street length: 8m
Street width: 4m

Distribution of displacements



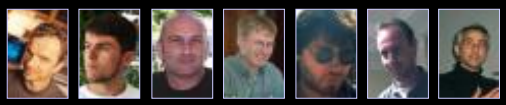
Moussaïd, M. *et al., PNAS* (2011)
Helbing, D. *et al., Physical Review E* (2007)

Conclusions

Collective behaviors in human crowds: from experiments to model

- Quantitative methods developed in social ethology can be used to investigate collective behaviors in human groups at least in simple situations
- The heuristics-based approach may inspire new models of collective human behavior (group decision making and social activity patterns), where the occurrence of simultaneous interactions between multiple individuals matters

Acknowledgements



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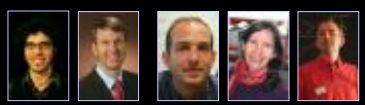
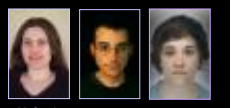
Laboratoire Plasma et Conversion d'Energie, CNRS, Université Paul Sabatier, Toulouse, France

Acknowledgments

PEDIGREE Project: Emergence of collective behavior among pedestrians: experiments and models



M. Moussaïd | D. Helbing | J. Pettré | C. Appert-Rolland | P. Degond



M. Combe | M. Moreau | E. Guillot