# CONGESTION AND PUSHING AT PEDESTRIAN BOTTLENECKS

MAY 19th, 2022 22nd Swiss Transport Research Conference

Mitglied der Helmholtz-Gemeinschaft

JÜLICH
Forschungszentrum

# OVERVIEW

## Introduction

- Congestion, capacity, motivation, competition and clogging

## Bottleneck capacity / flow

- Influence of width and length
- Influence of motivation

## Density in front of the bottleneck

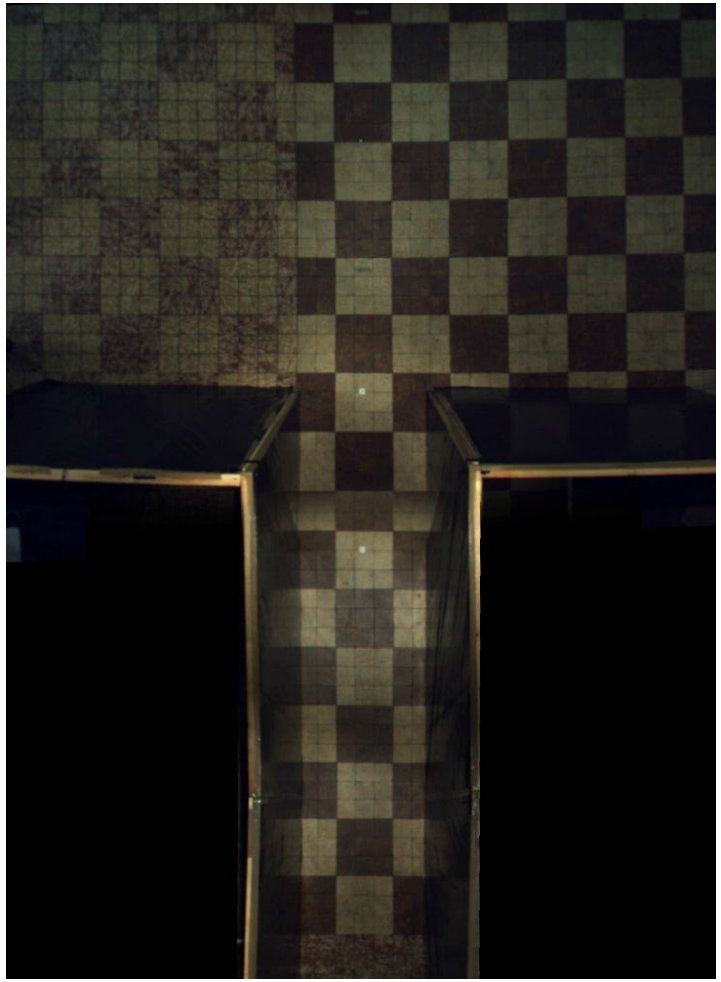
- Experiment I: Social norms and fairness
- Experiment II: Science and social psychology

## Summary and outlook

# INTRODUCTION

## Process and definitions

- Unidirectional movement of pedestrian passing a bottleneck
- Incoming flow $J_{in}$ outgoing flow $J_{out}$
- Width / length of the bottleneck
- Width of the room / corridor leading the bottleneck



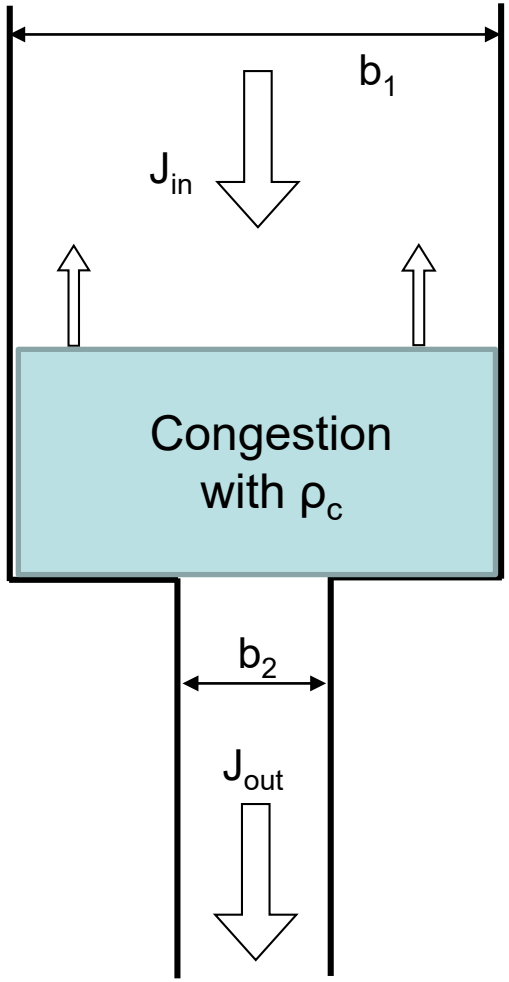
# INTRODUCTION

## Process and definitions

- Unidirectional movement of pedestrian passing a bottleneck
- Incoming flow $J_{in}$ outgoing flow $J_{out}$
- Width / length of the bottleneck
- Width of the room / corridor leading the bottleneck

## Phenomena

- $J_{in} > J_{out}$ : Congestion
- Density increases till a certain threshold $\rho_c$, then the congested area grows in the opposite direction of movement
- Clogging could happen



# INTRODUCTION - COMPETITION AND COOPERATION

## Clogging at bottlenecks

Experiments performed in October 2021 as part of the project CrowdDNA (EU H2020 FET Open)

https://crowddna.eu/

# INTRODUCTION - COMPETITION AND COOPERATION

## Social norms: queuing, giving way or pushing

https://youtu.be/xG-meaGqg-M

https://youtu.be/IFFCLtCB7Ag

# INTRODUCTION

## The experiment of Mintz*

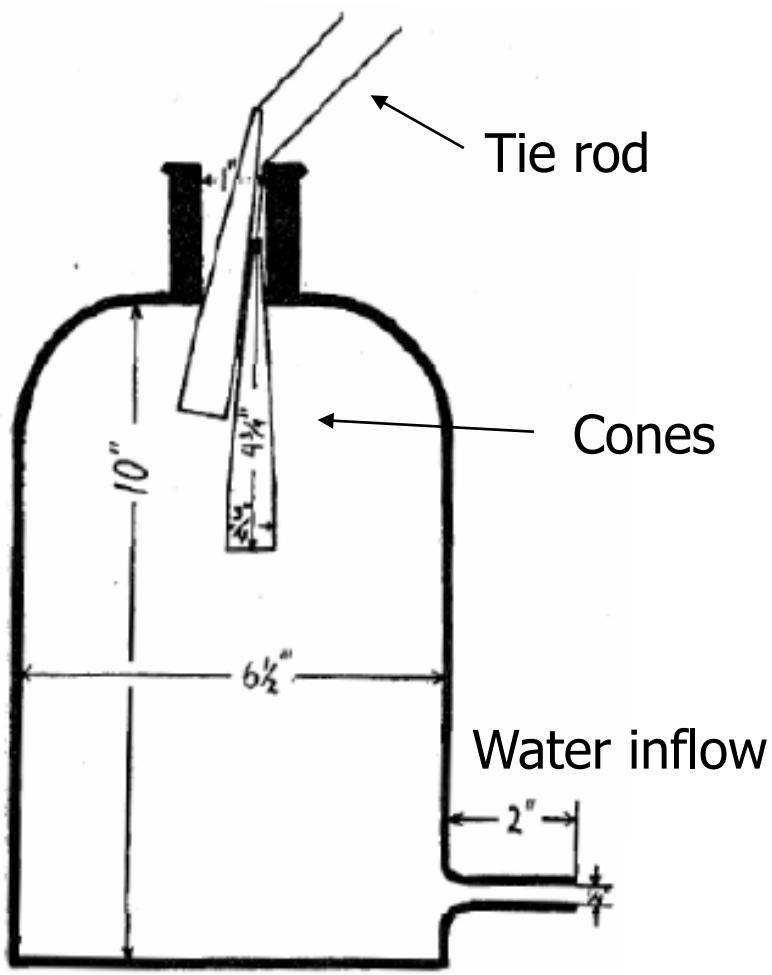
- Groups of 15-21 students
- Task: Pulling out cones dry
- Only one cone at a time - otherwise clogging

## Different setups and instructions

- With and without individual rewards (little money)
- With and without the opportunity to discuss
- With and without special arousal (swearing and noise)

Without reward: No clogging

**With reward: clogging**




* A. Mintz, Non-adaptive group behaviour, The Journal of abnormal and social psychology 46 150 (1951)

# INTRODUCTION

## Cooperation at bottlenecks

- Mostly people cooperate (weak incentive, no reward) by keeping distance, giving way or stopping
- In a cooperative setting clogging is very unlikely (only by chance or by misunderstandings)

## Competition at bottlenecks

- High motivation due to incentives or rewards trigger competitive behavior
- In crowds the incentives initiating competition could be seemingly small (e.g. a place in a train, a bargain on sail, … ) but also very high (e.g. survival in a dangerous situation)
- With a high motivation people move fast, get closer and fill gaps, or even start to compete by pushing and shoving using their elbows

## Competition, clogging and flow

- Due to the competitive behavior the probability of clogs increase
- But even if the probability of clogs increase, it is an open question whether the flow decrease in comparison to a cooperative setting

# INTRODUCTION

## Questions

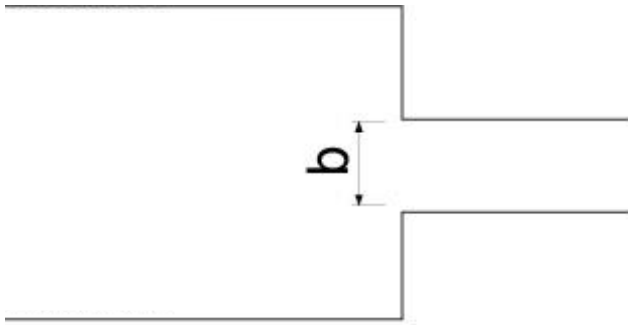
1. Influence of
   - spatial structure of the boundaries
   - motivation (triggered by incentives / rewards)

   on
   - Capacity, probability of clogs, density in front of the bottleneck

2. Relation of social psychological factors, like social norms, with the spatial structure of a bottleneck

# Bottleneck flow - influence of width and length

# CAPACITY OF A BOTTLENECK




## HG (Laboratory experiment)

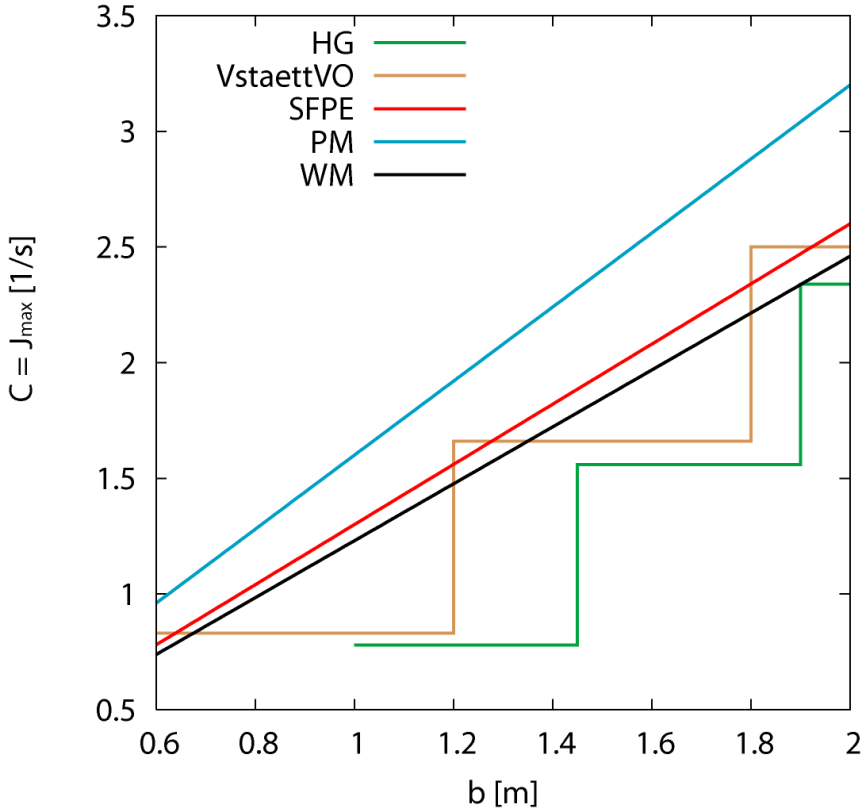
- Formation of lanes
- Lane distances independent of b

→ C increases stepwise

## SFPE, WM, PM

- $C_s$ = C/b independent of b

→ C increases linearly

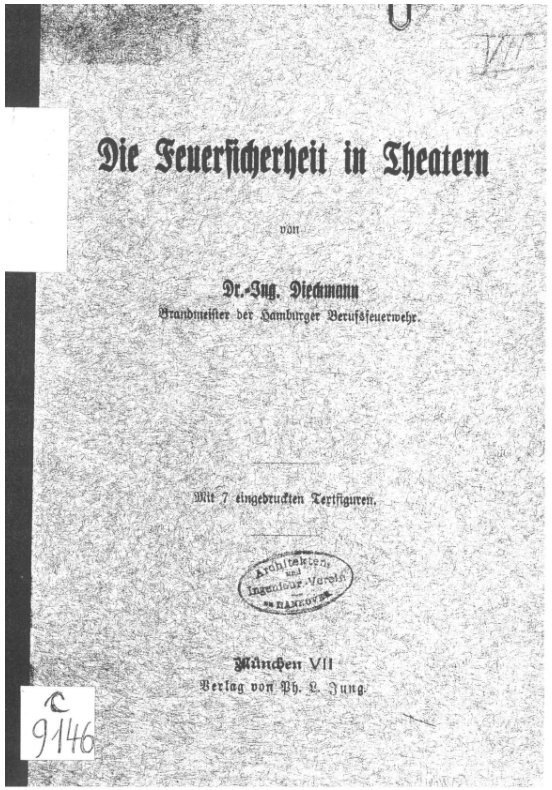



SFPE: P. J. DiNenno (1995)
PM: V. M. Predtechenskii et al. (1978)
WM: U. Weidmann (1993)
HG: S.P.Hoogendoorn et al. (2005)
VstättVO: ARGEBAU

# C(b) STEPWISE OR CONTINUOUS?

## Dieckmann: C(b) stepwise

## Fire safety in theaters (1911)



Die Feuersicherheit in Theatern

von

Dr.-Ing. Dieckmann

Brandmeister der Hamburger Berufsfeuerwehr.

Mit 7 eingedruckten Textfiguren.



München VII

Verlag von Ph. C. Jung.



## Fischer: C(b) almost continuously

## Phd Thesis (1933)

Über die Leistungsfähigkeit
von
Türen, Gängen und Treppen
bei
ruhigem, dichtem Verkehr.

Von der Sächsischen Technischen Hochschule zu Dresden
zur Erlangung der Würde eines Doktor-Ingenieurs
genehmigte Dissertation.

Vorgelegt von
Dipl.-Ing. Herbert Fischer
aus Döbeln/Sa.

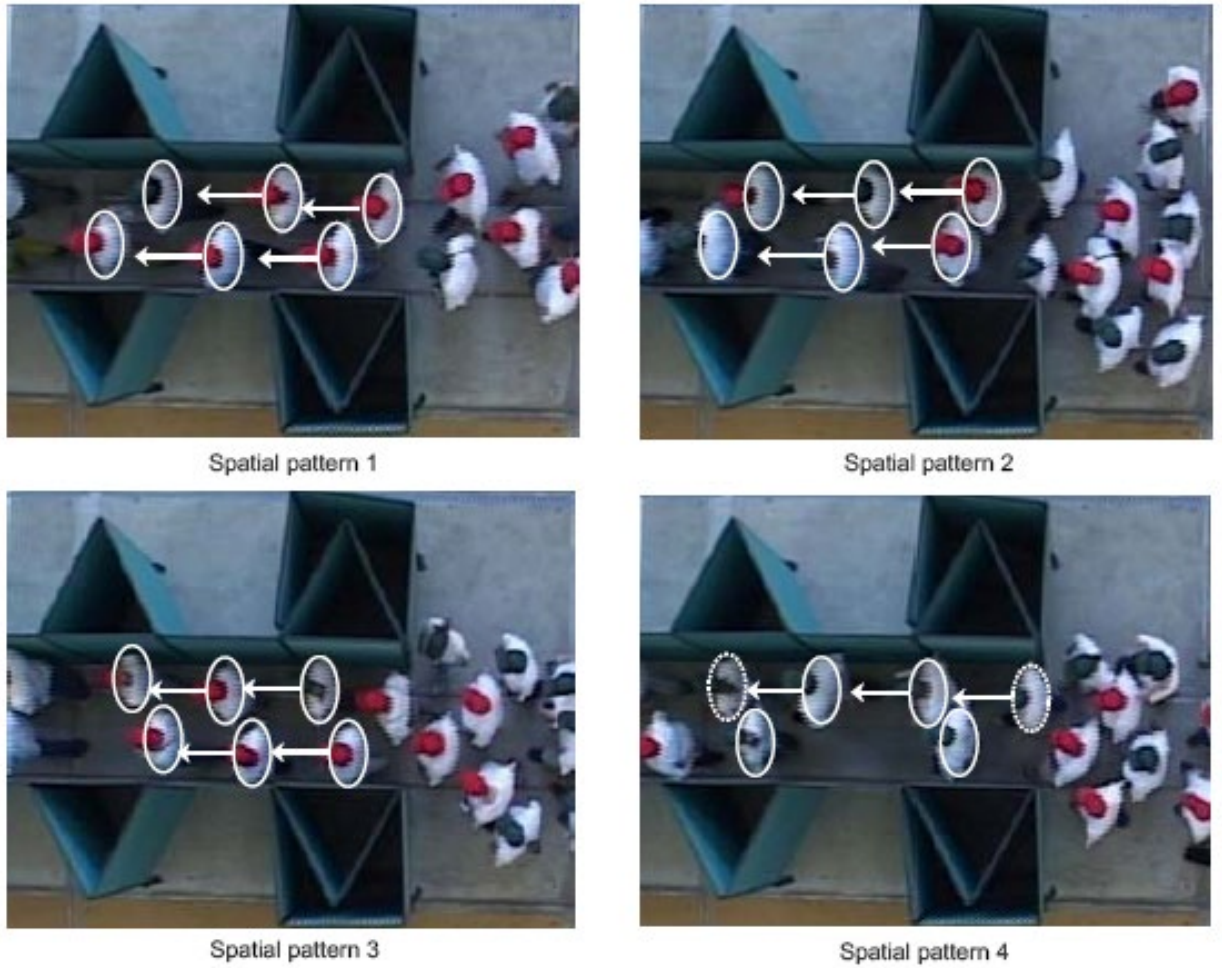


Referent: Professor Wilhelm Jost.
Korreferent: Professor Dr. phil. Walter Blumenfeld.
Eingereicht: 18. Juli 1932.
Tag der mündlichen Prüfung: 14. Januar 1933.

# C(b) STEPWISE OR CONTINUOUS?

## Hoogendoorn und Daamen (2005)*

Zipper effect!




*Hoogendoorn, S. P. & Daamen, W. Pedestrian behavior at bottlenecks *Transport. Sci., 39*, 147-159 (2005)

# C(b) STEPWISE OR CONTINUOUS?

## Hoogendoorn und Daamen (2005):

Pedestrian behavior at bottlenecks

The capacity C increases only if an additional lane emerges.

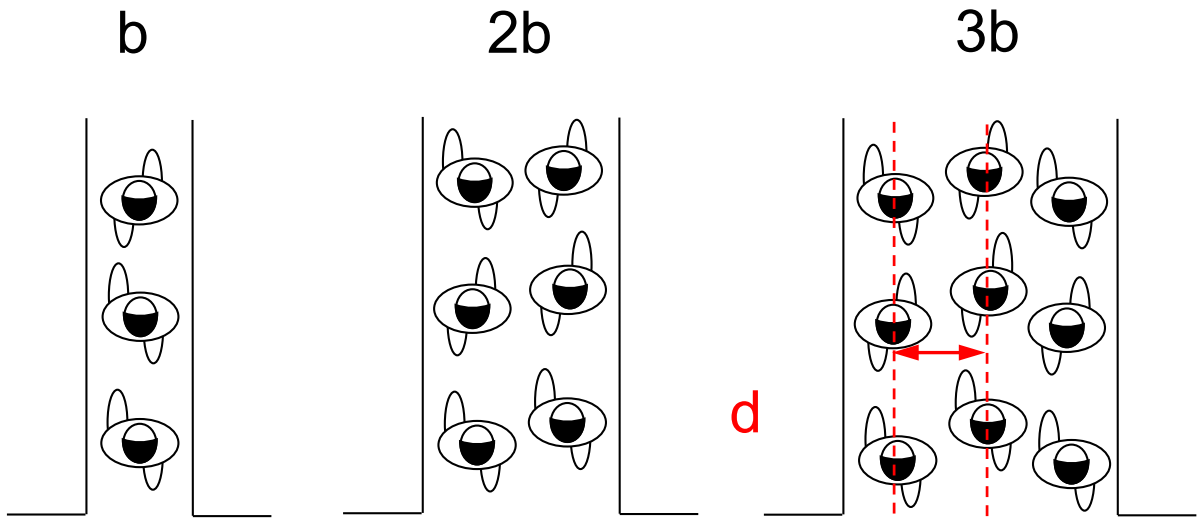
n: number of lanes

$$C = C_{lane}\ n$$

Stepwise increase of C with b

Implication for lane distances d

d does not depend on b!




*Hoogendoorn, S. P. & Daamen, W. Pedestrian behavior at bottlenecks *Transport. Sci., 39*, 147-159 (2005)

# EXPERIMENT

## Bottleneck flow*,**

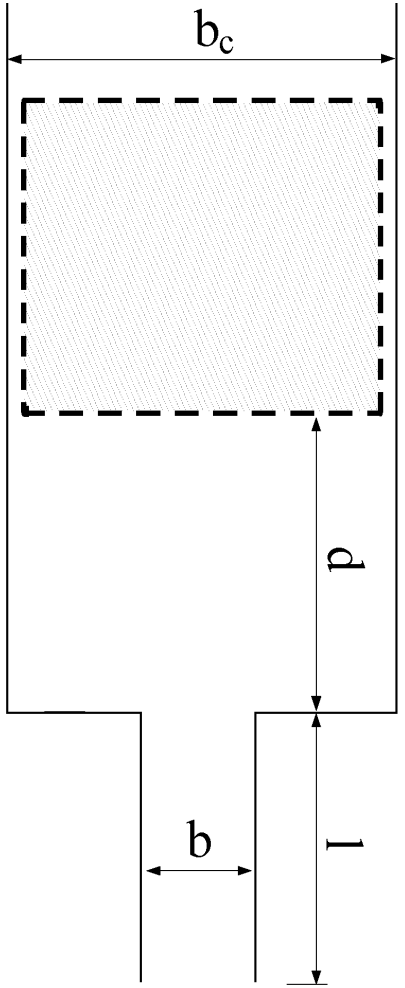
- Bottleneck width b

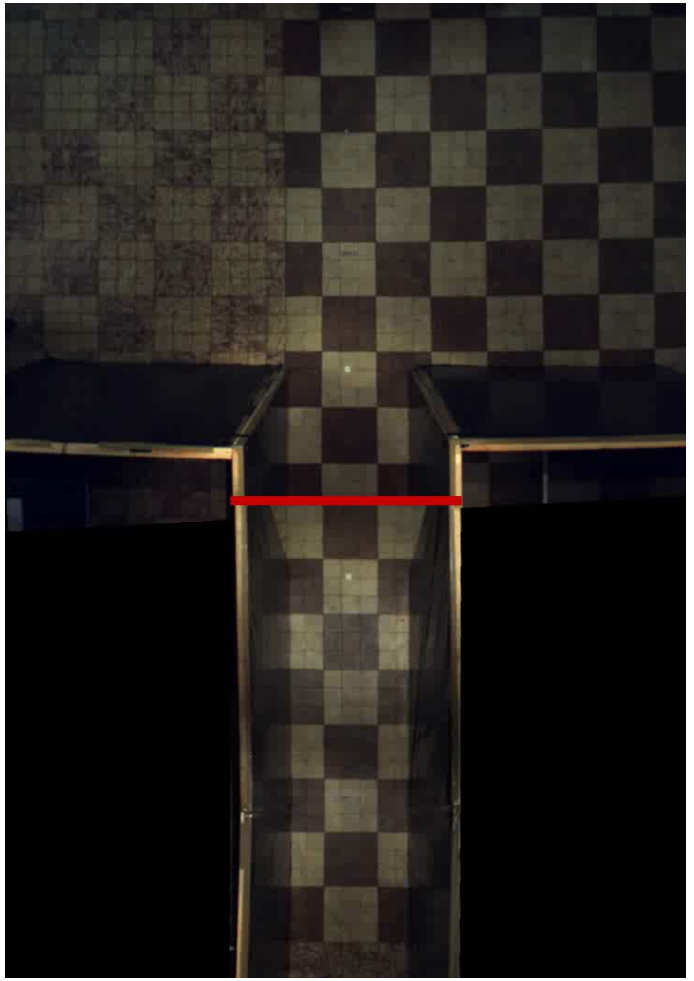
  0.8, 0.9, 1.0, 1.1, …, 2.5 m

- Bottleneck length l

  0.1, 2.0, 4.0 m

- Corridor width $b_C$
- …

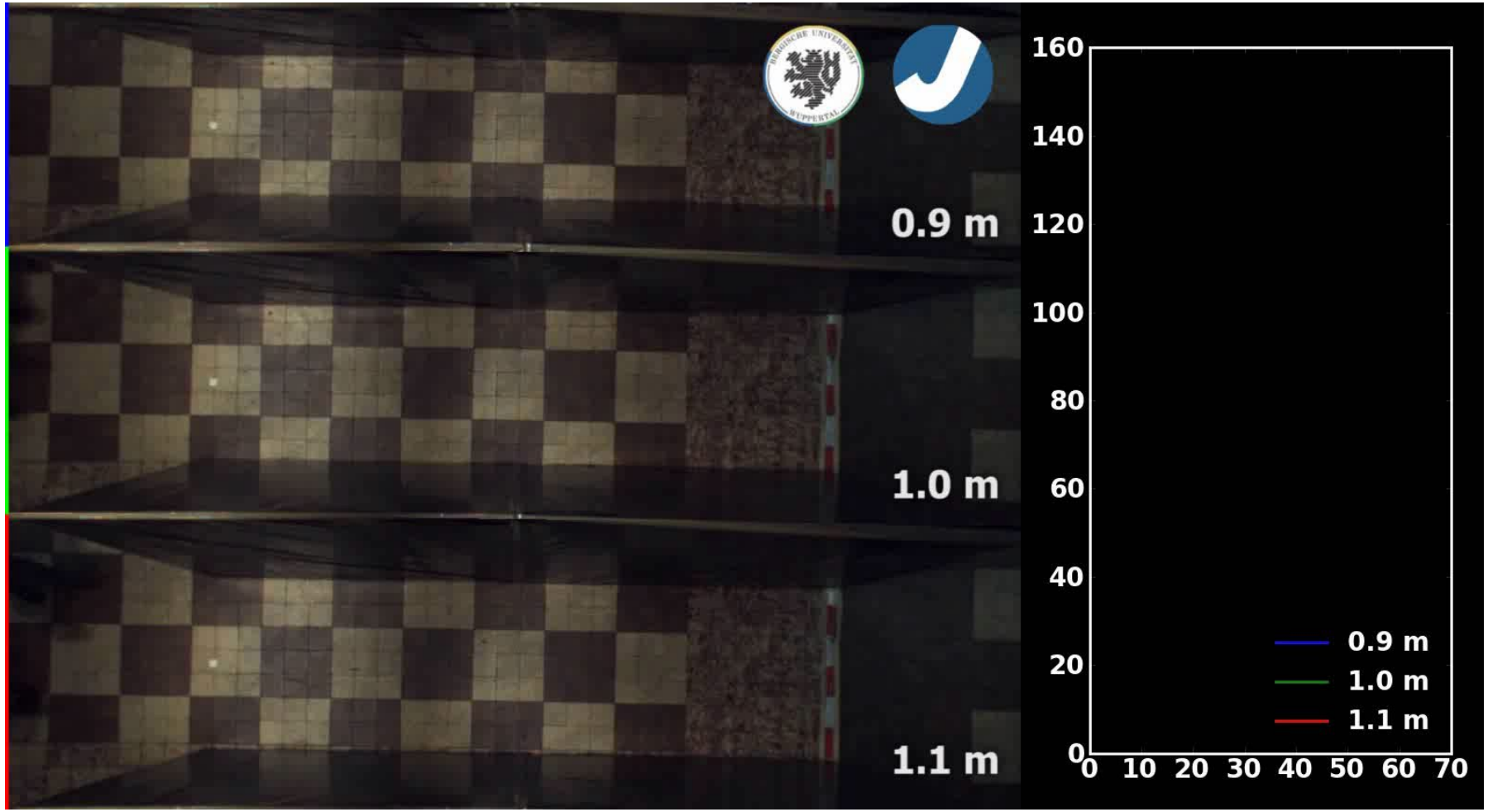


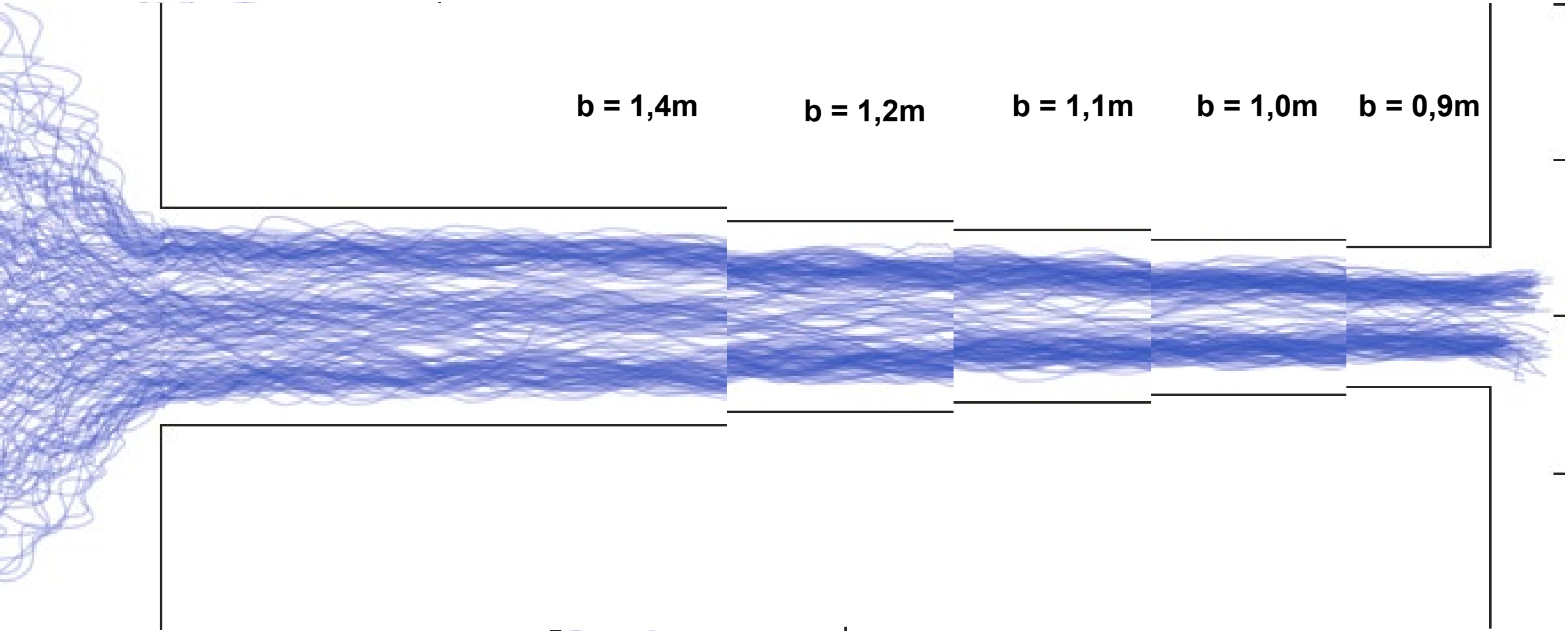
*Seyfried, A. et al. New insights into pedestrian flow through bottlenecks Transportation Science, 2009, 43, 395-406

**Liddle, J. et al. Microscopic insights into pedestrian motion through a bottleneck, resolving spatial and temporal variations ArXiv, 2011

# CAPACITY OF A BOTTLENECK



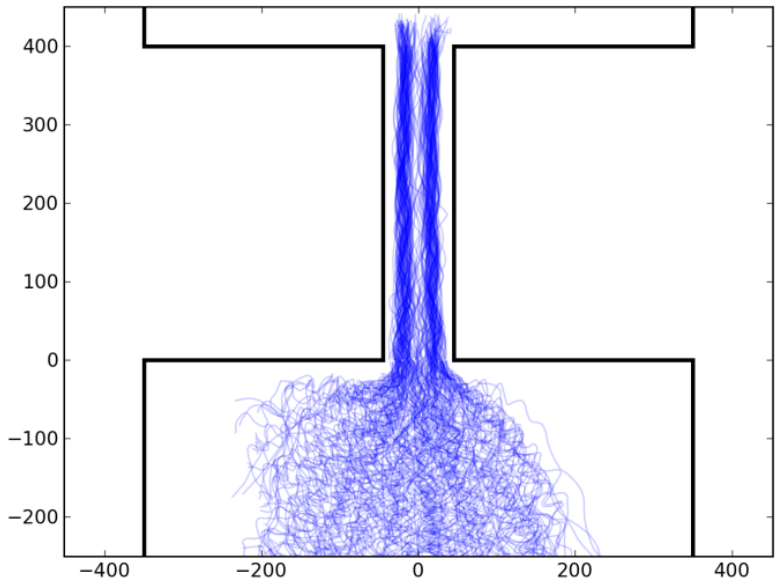
# LANE DISTANCE

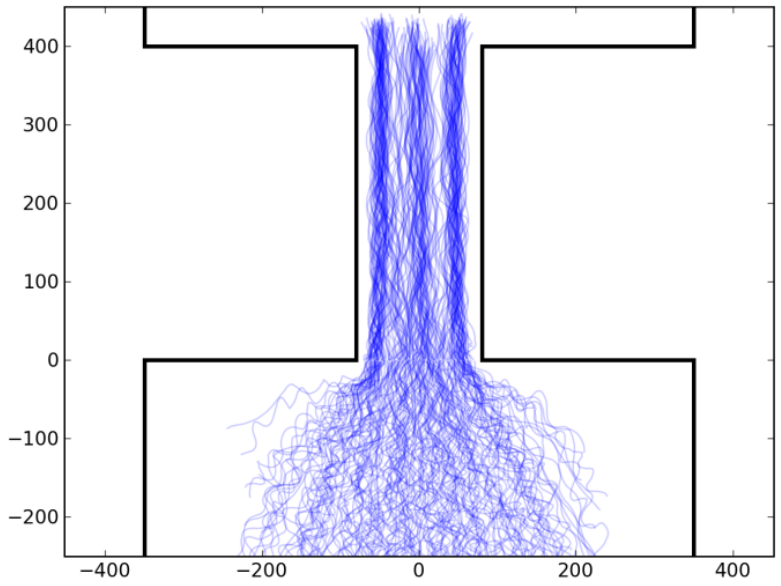


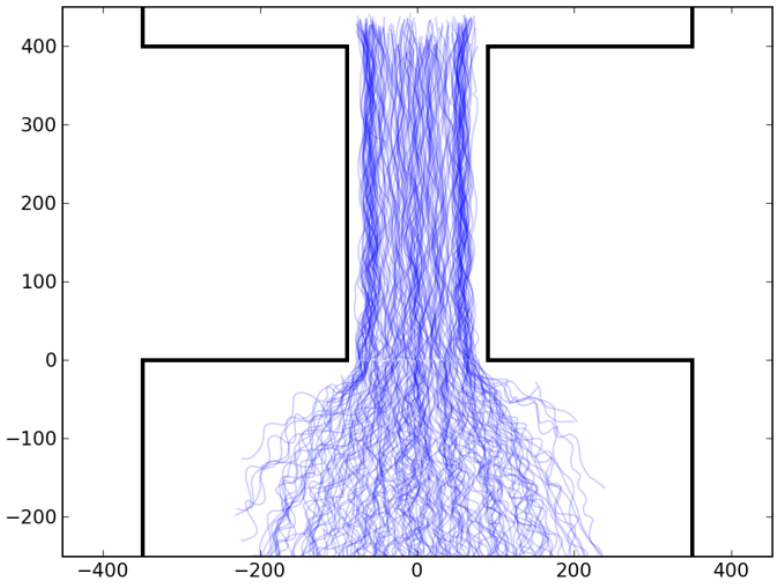
# LANES IN MIDDLE DISAPPEAR FOR WIDE BOTTLENECKS

## Is the formation of lanes due to the zipper effect?

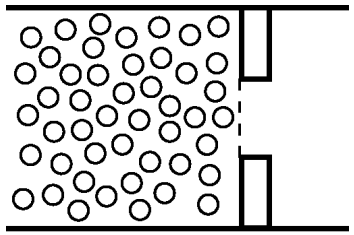
- At wide bottlenecks the lane in the middle disappear.
- Lanes in cumulative trajectories appear at the boundaries only.
- It’s not necessarily a consequence of the zipper effect!



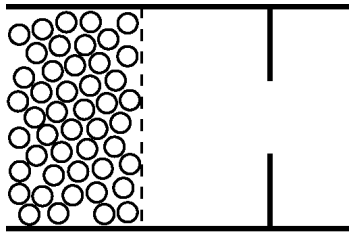



# CAPACITY OF A BOTTLENECK: C(b)



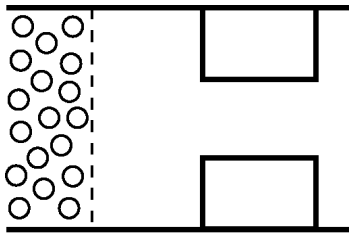
**Kretz et al.**

J. Stat. Mech., P10014 (2006)



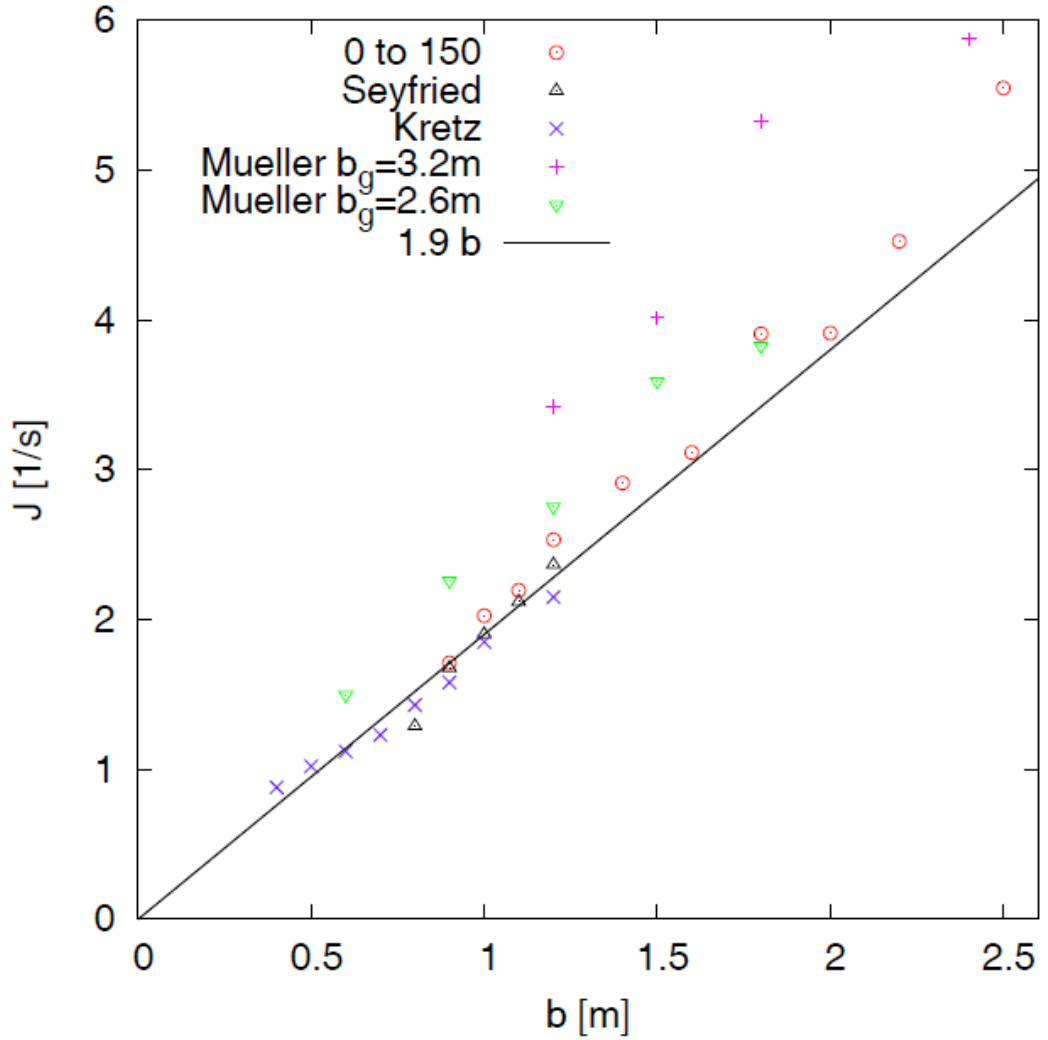
**Mueller K.**

Dissertation, Magdeburg (1981)



**Seyfried et al.**

Trans. Sci., 43, 395-406 (2009), …



# Bottleneck flow – influence of motivation

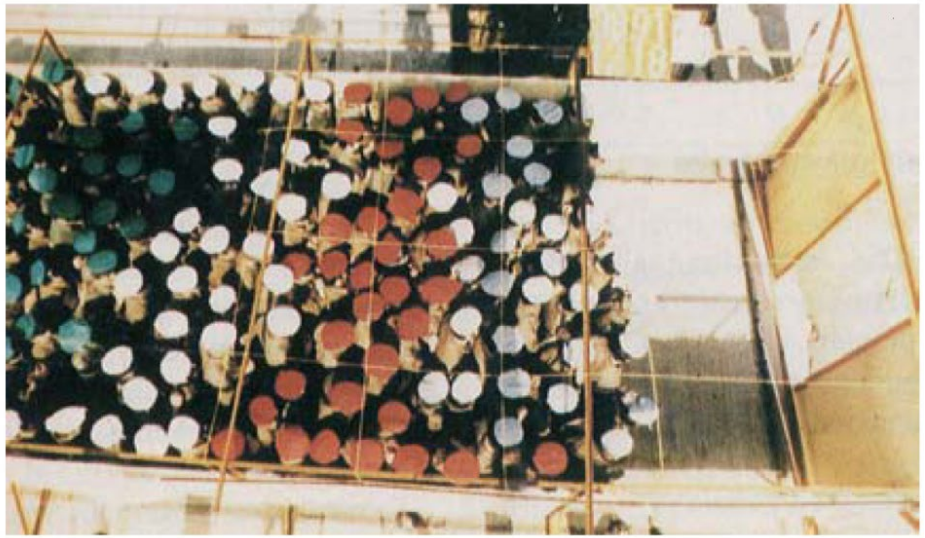
# EXPERIMENTS MÜLLER, 1981*

## Variations of

- N = [150,190] test persons (soldiers)
- Width of the corridor $b_{cor}$
- Width of the bottleneck $b_{bck}$

## Instruction to the test persons

- Normal: smooth movement, mutual consideration
- Danger: run for you lives



*K. Müller, Die Gestaltung und Bemessung von Fluchtwegen für die Evakuierung von Personen aus Gebäuden, Dissertation Technische Hochschule Magdeburg 1981

# EXPERIMENTS MÜLLER, 1981*

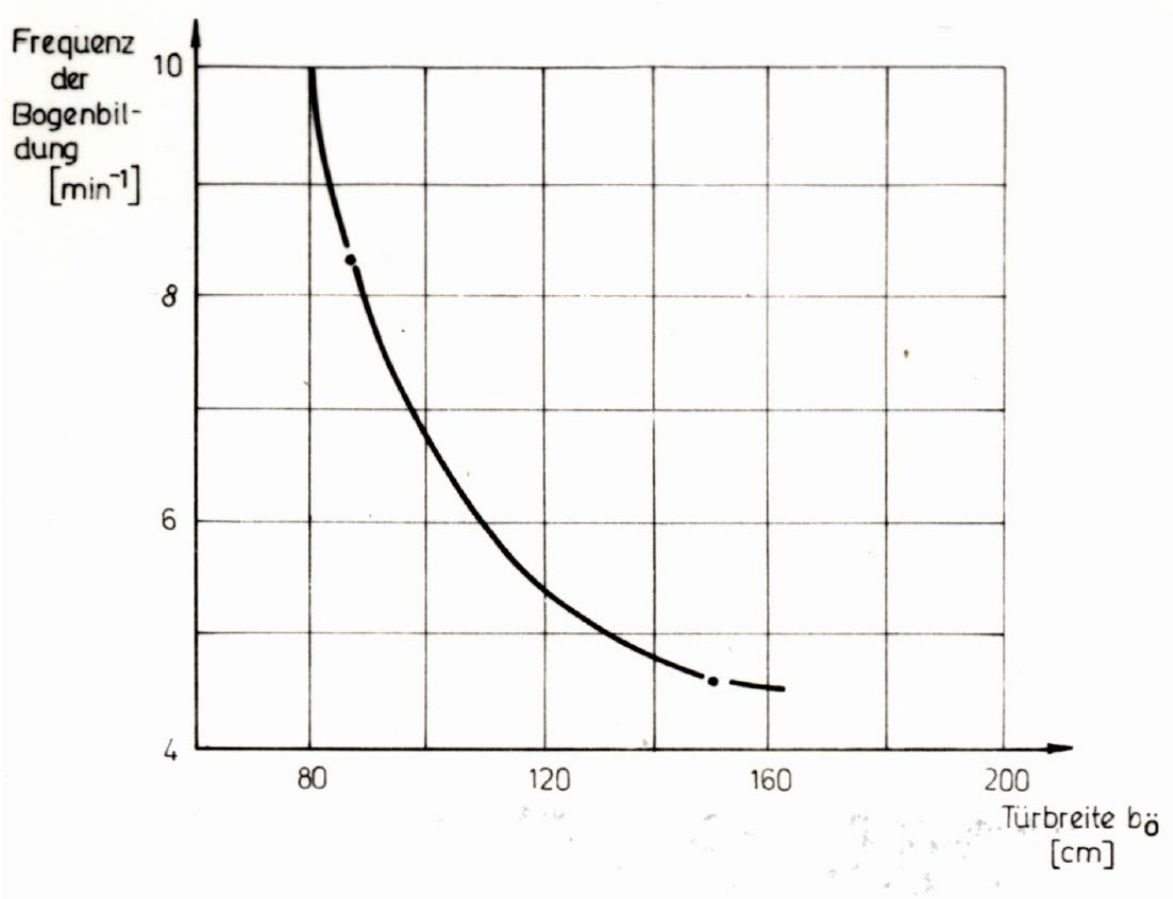
The frequency of clogs appearing at competitive settings depend on the width of the bottleneck

## Clogging

- $b_{bck} \leq 1.1$ m: clogs in short frequencies. Flow stops temporarily
- $b_{bck} \approx 1.2$ m: Pulsing flow
- $b_{bck} \geq 1.6$ m: No clogs observable, fluent and homogenous flow

## Results for the capacity

- For every $b_{cor}$ and every $b_{bck}$ the clearance time ($t_{evak} = 1/C$) was significantly smaller for runs with high motivation -> The capacity C was higher!



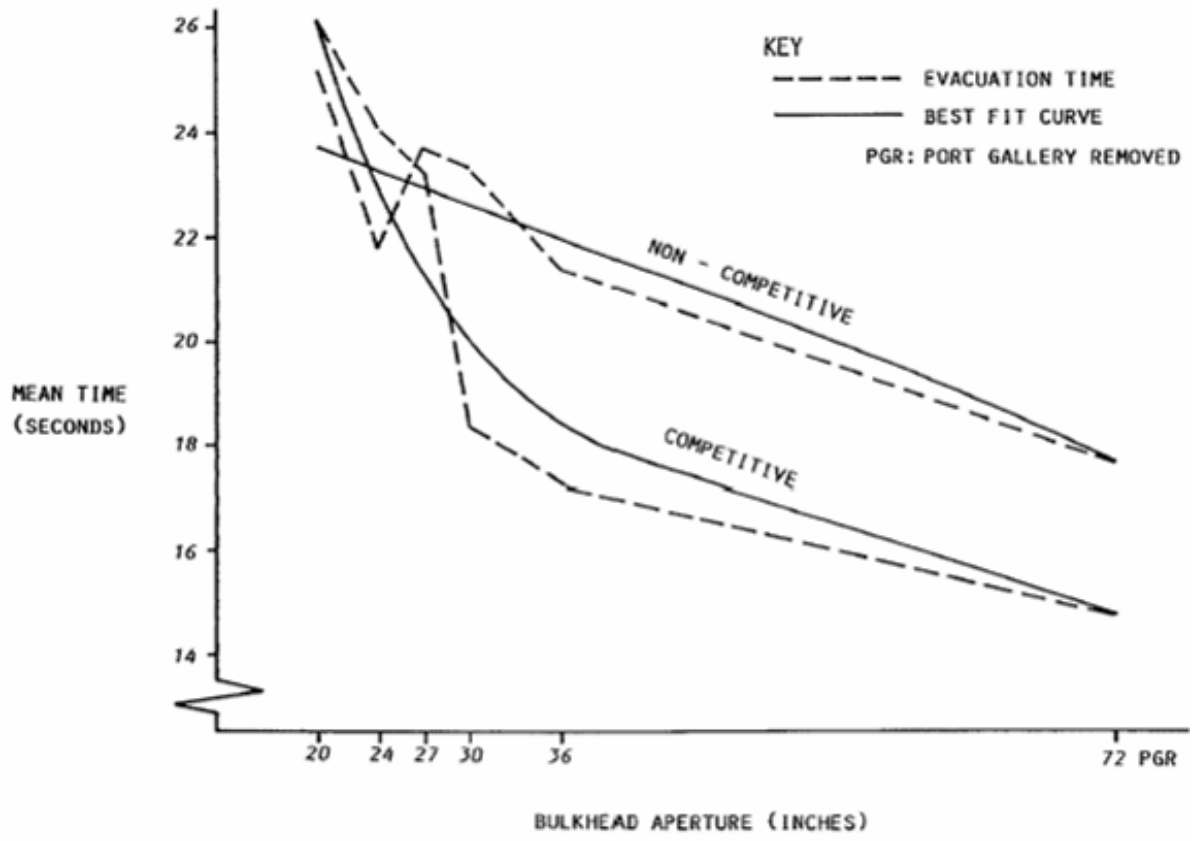
# EXPERIMENTS MUIR ET AL. 1996*

The frequency of clogs appearing at competitive settings depend on the width of the bottleneck

## Clogging and capacity

- Variations of the bottleneck width (gallery kitchen)
- For small widths (arcs and clogging) non competitive runs are faster
- For large widths competitive runs are faster
- Crossover of $t_{evak}$ at small widths

$$C = \frac{1}{t_{evak}}$$




*Muir et al., Effects of Motivation and Cabin Configuration on Emergency Aircraft Evacuation Behavior and Rates of Egress, The Int. J. of Aviation Psychology, 6, 1996

# EXPERIMENTS GARCIMATIN ET AL. 2016*

## Three level of competitiveness: low, medium and high

- Two door width 0,69 m (SD) and 0,75 m (LD)
- Instruction: Exit the room and follow these rules
  - Low: avoid intentional contact (LC)
  - Medium: soft physical contact is allowed (MC)
  - High: moderate pushing is allowed (HC)

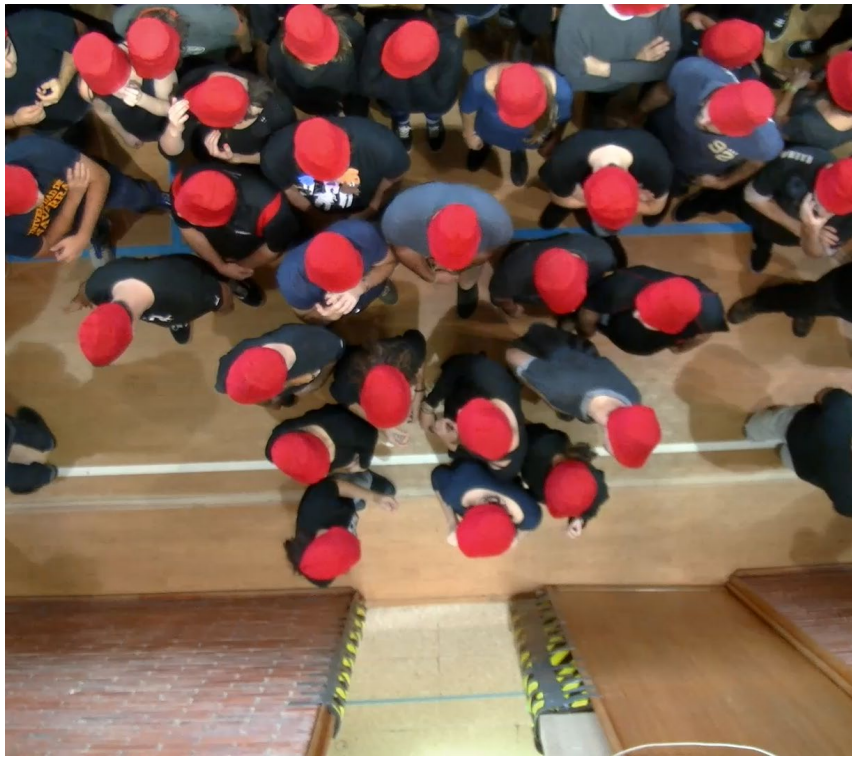
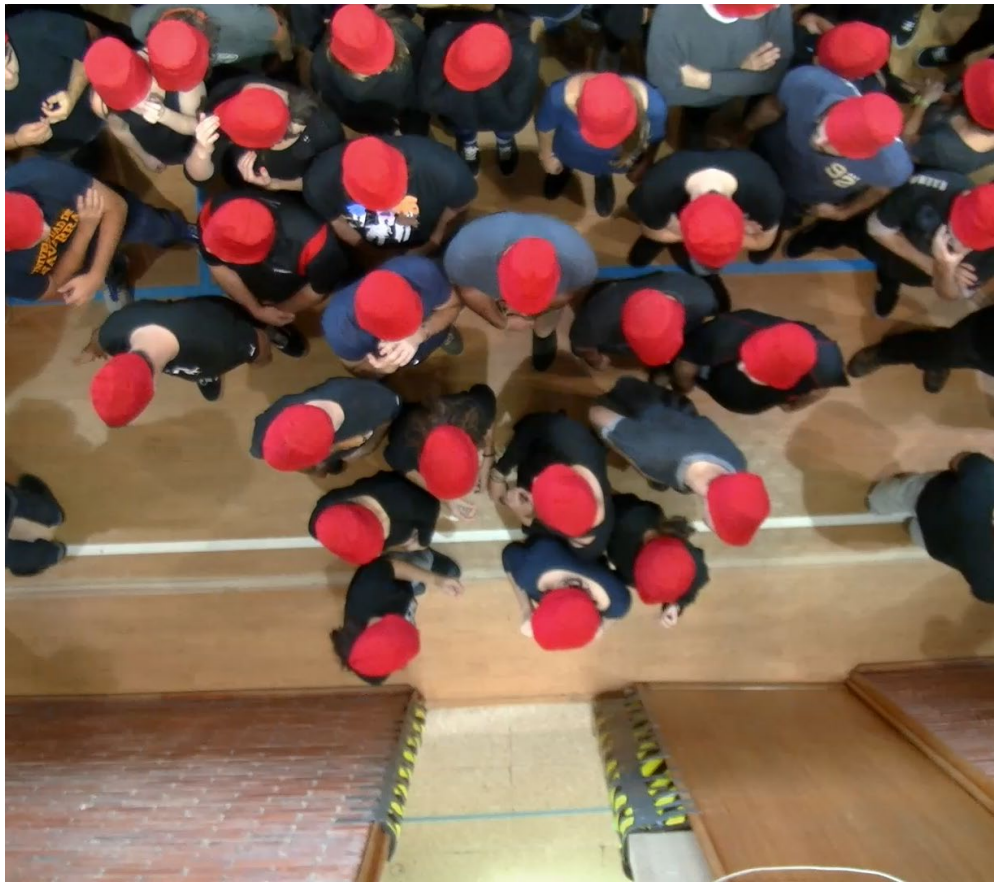


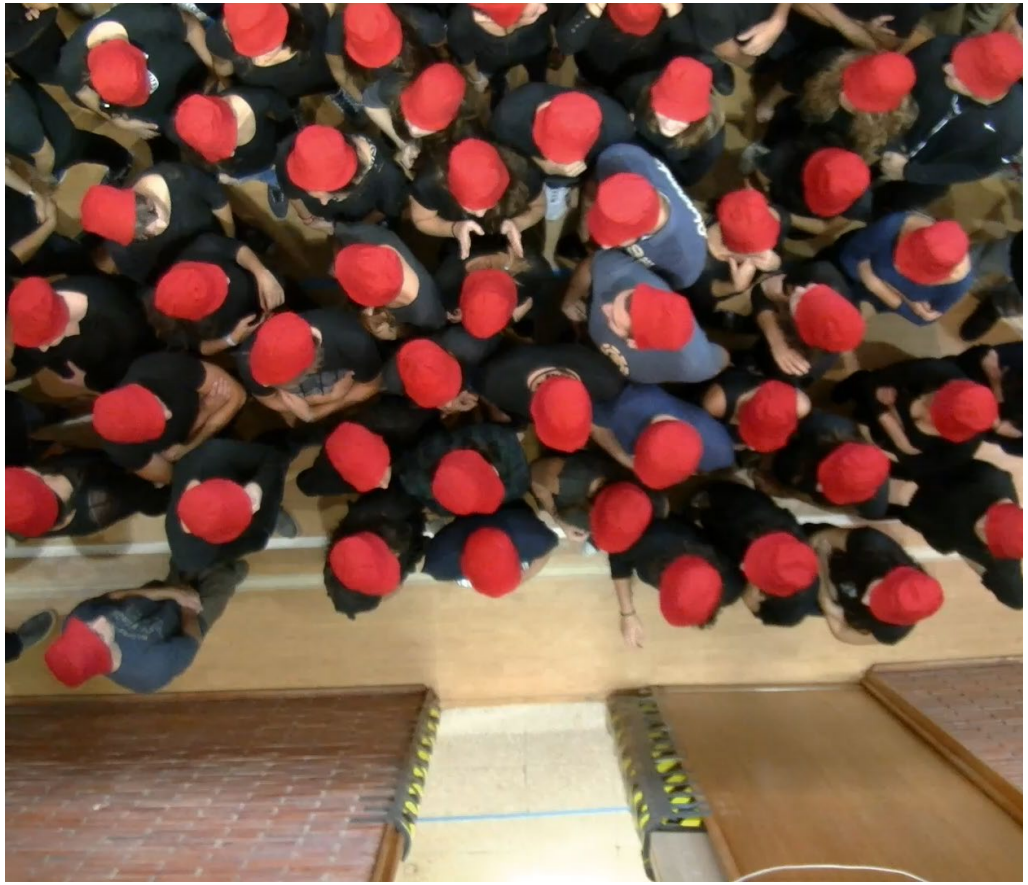
**Table 1.** Number of runs and passage times for each experimental situation.

| | LD HC | LD LC | SD HC | SD MC | SD LC |
|---|---|---|---|---|---|
| Number of runs | 8 | 5 | 13 | 10 | 10 |
| Total number of passage times | 682 | 420 | 1241 | 970 | 920 |

*Garcimartín, Parisi, Pastor, Martín-Gómez, Zuriguel, Flow of pedestrians through narrow doors with different competitiveness, J. Stat. Mech, 043402, 2016

# EXPERIMENTS GARCIMATIN ET AL. 2016*





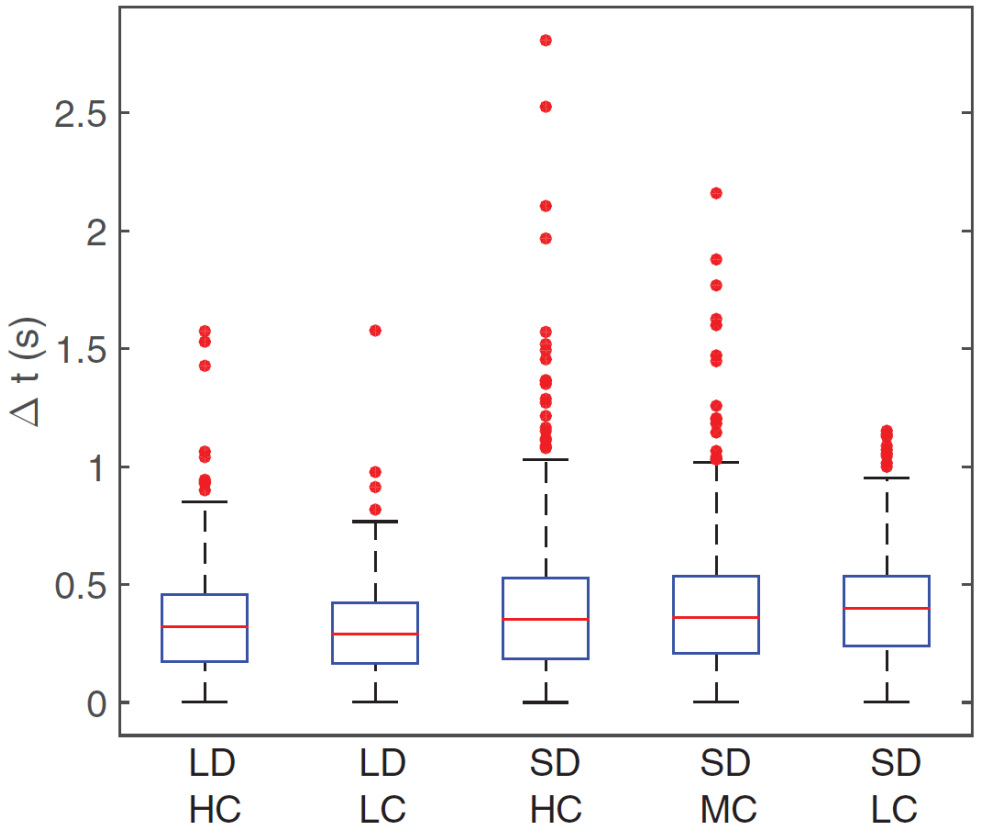
*Garcimartín, Parisi, Pastor, Martín-Gómez, Zuriguel, Flow of pedestrians through narrow doors with different competitiveness, J. Stat. Mech, 043402, 2016

# EXPERIMENTS GARCIMATIN ET AL. 2016*

- The probability of clogs increases leading to extreme events with large interruptions of the flow $\Delta t$

$$C = \frac{1}{\Delta t}$$

- But even if high competition increase the probability of clogs, it does not change the flow significantly

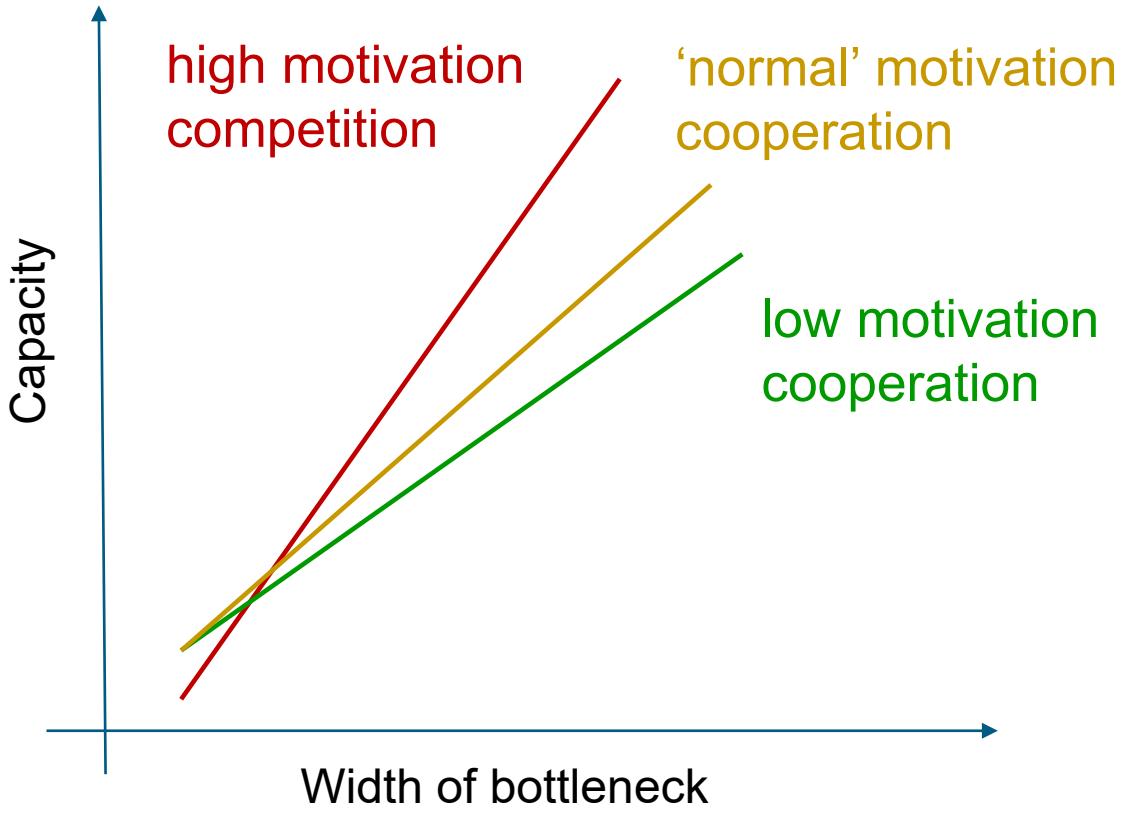



*Garcimartín, Parisi, Pastor, Martín-Gómez, Zuriguel, Flow of pedestrians through narrow doors with different competitiveness, J. Stat. Mech, 043402, 2016

# BOTTLENECK FLOW, MOTIVATION AND CLOGGING

## Summary

- In general a high motivation improves the flow (people move faster, fill gaps, get closer)
- High motivation and competition could increase the probability of clogs
- Probability of clogs depend on the width of the bottleneck. At wide bottlenecks the probability is very low. Only for small width clogging could reduce the capacity
- **A negative effect of motivation on the flow is only evident at bottlenecks of small width (b ≈ < 1 m) and in competitive settings**



# Density in front of the bottleneck - Experiment I

Anna Sieben, Jette Schumann, Armin Seyfried
Collective phenomena in crowds –
Where pedestrian dynamics need social psychology,
PLoS ONE 12(6): e0177328, 2017

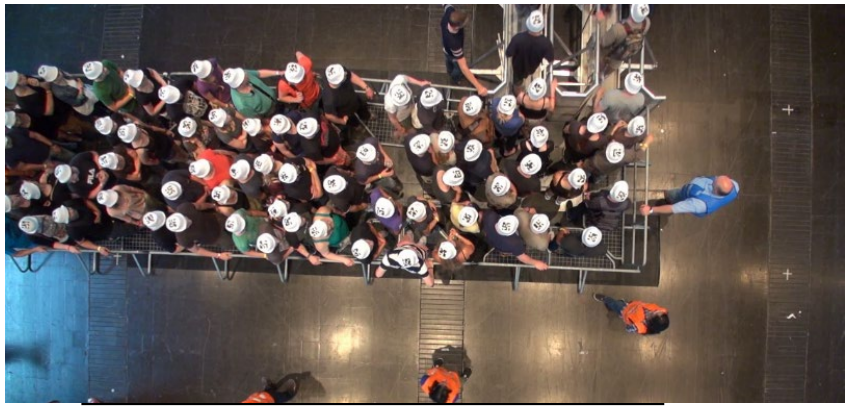
# PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

## Spatial structure of the barriers

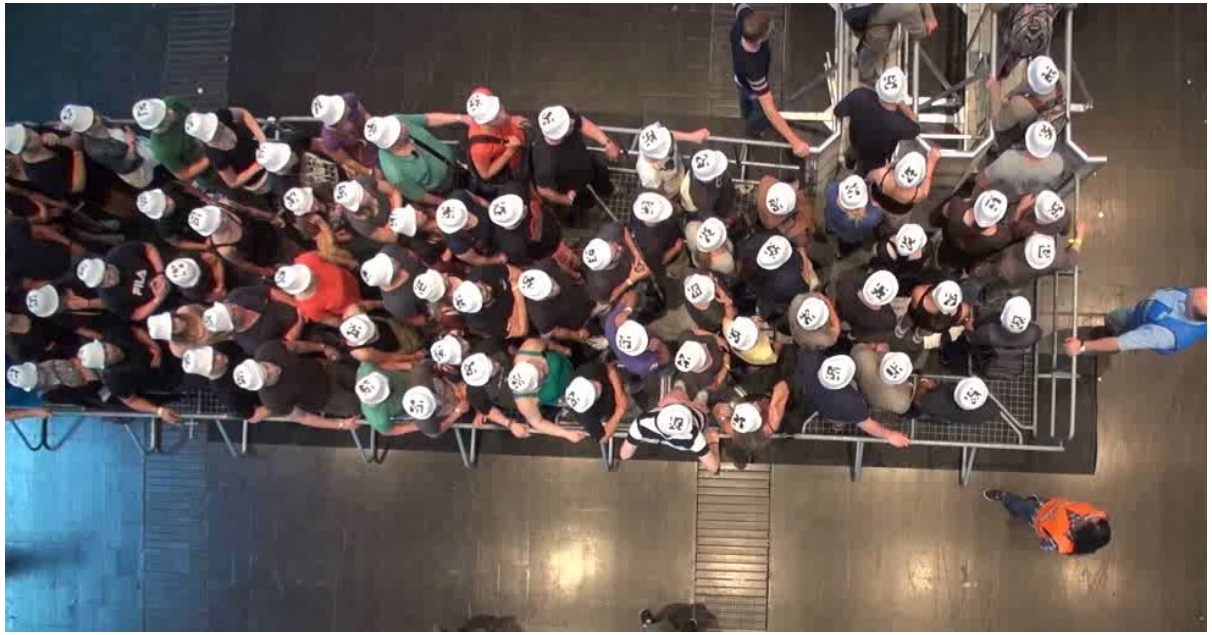
- Simple barrier with entrances,
  Test persons form a semicircle
- Corridor leading to the entrances

## Instruction to test person

- "… concert of your favorite artist …
  you want to get a place close
  to the stage … try to be one of the
  first passing the entrance..."

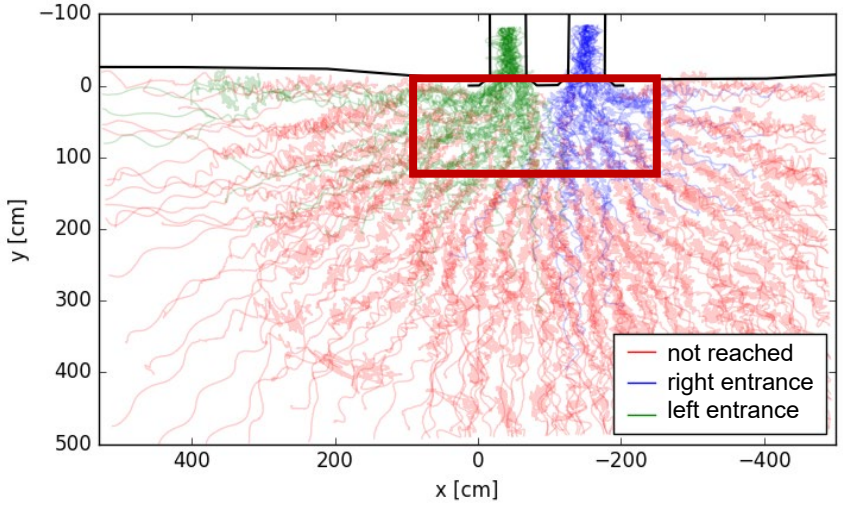


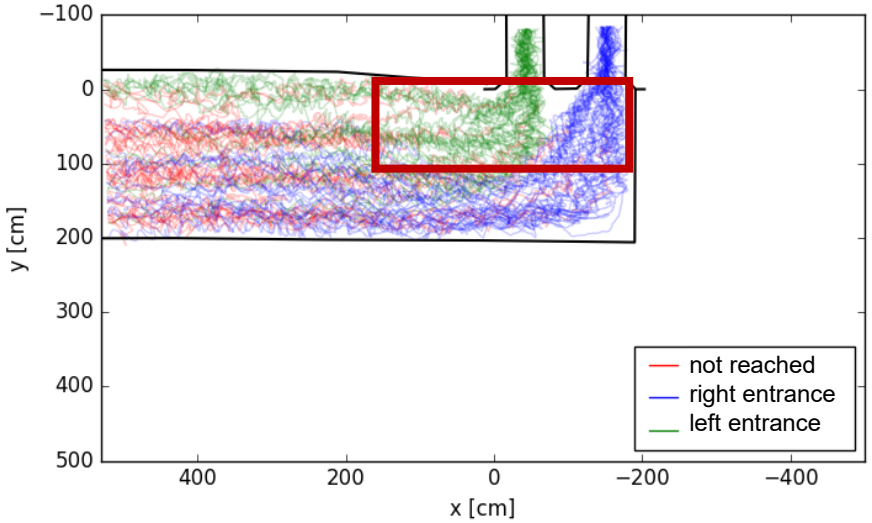
# PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

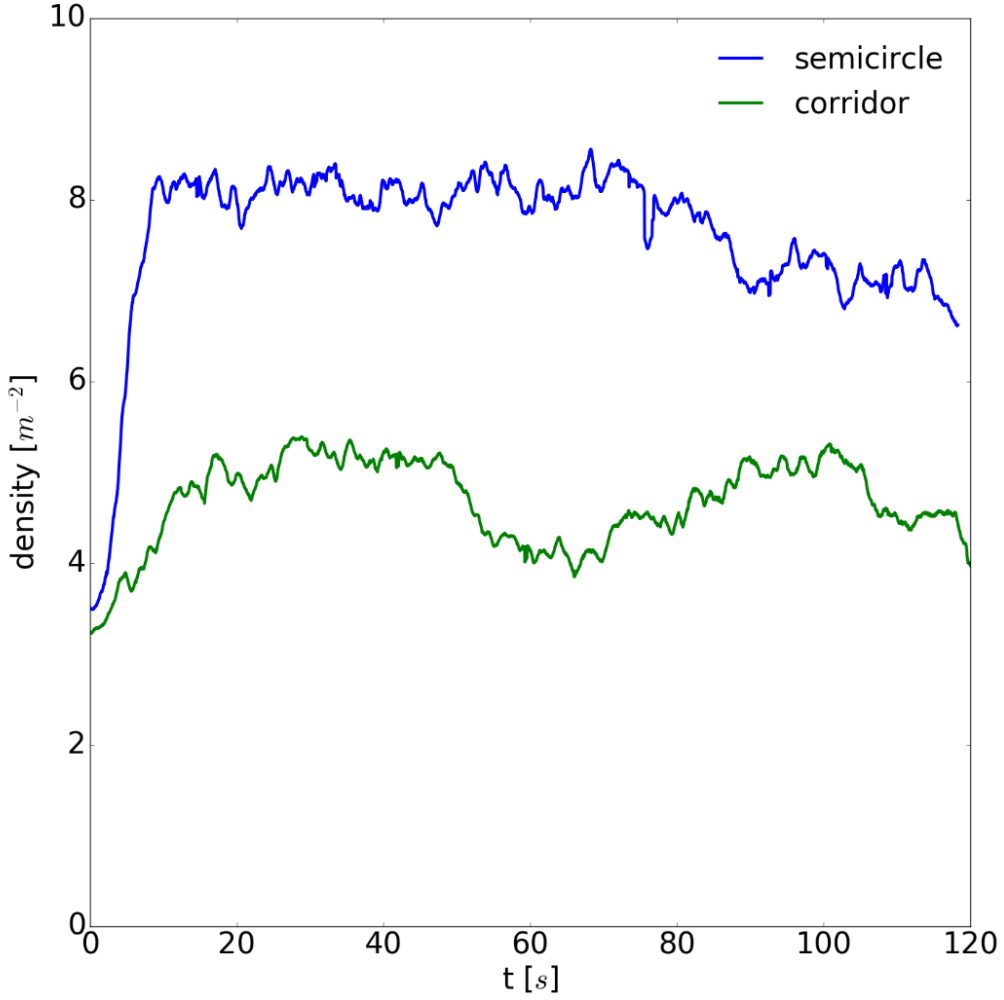


# PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

## Trajectories and time series of the densities



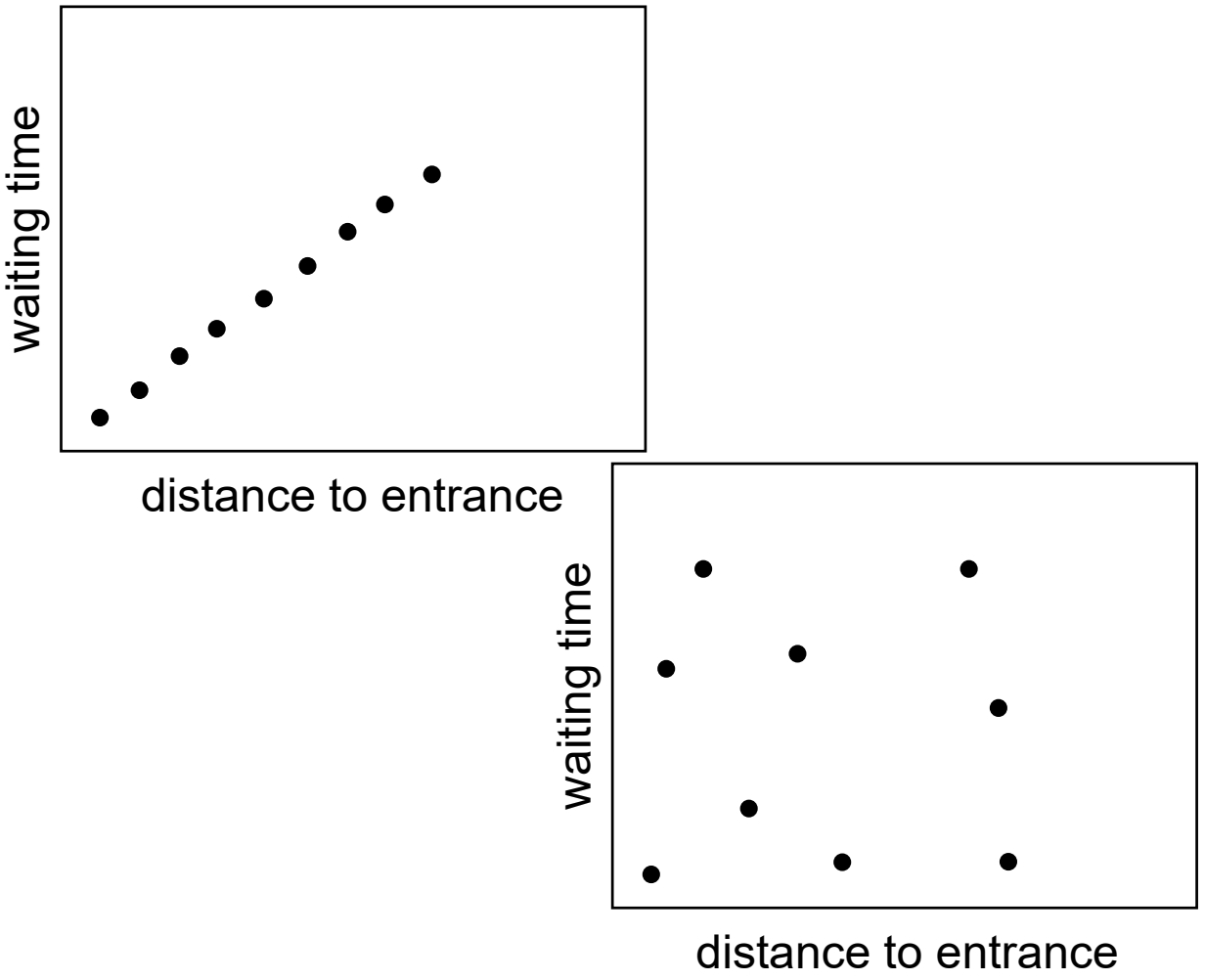



# PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

## Fairness

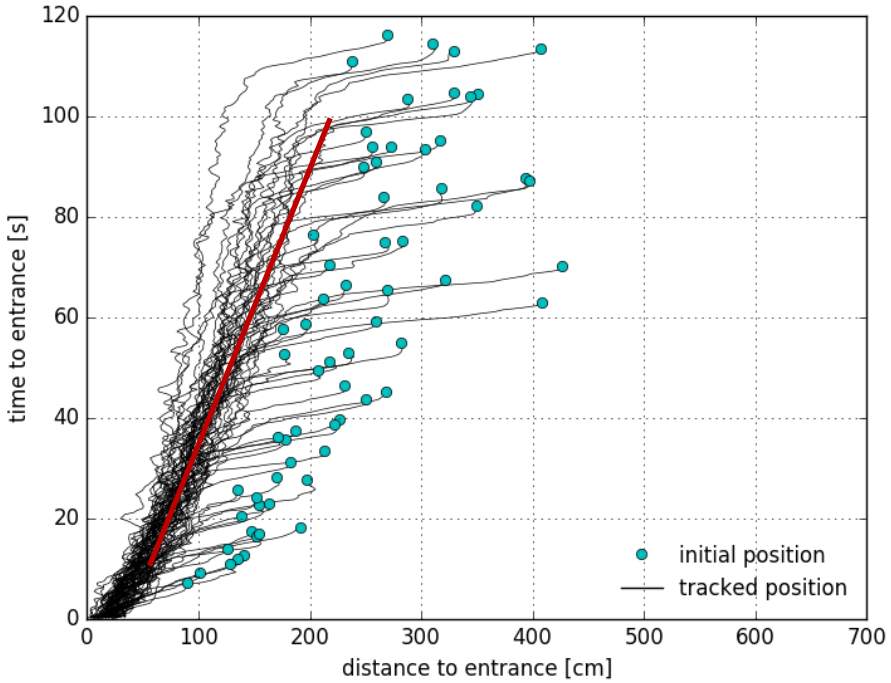
- (given a position at t=0 in front of the entrance)
- Correlation between waiting time and distance to the entrance
- Fair procedure -> strong correlation
- Unfair procedure -> no correlation



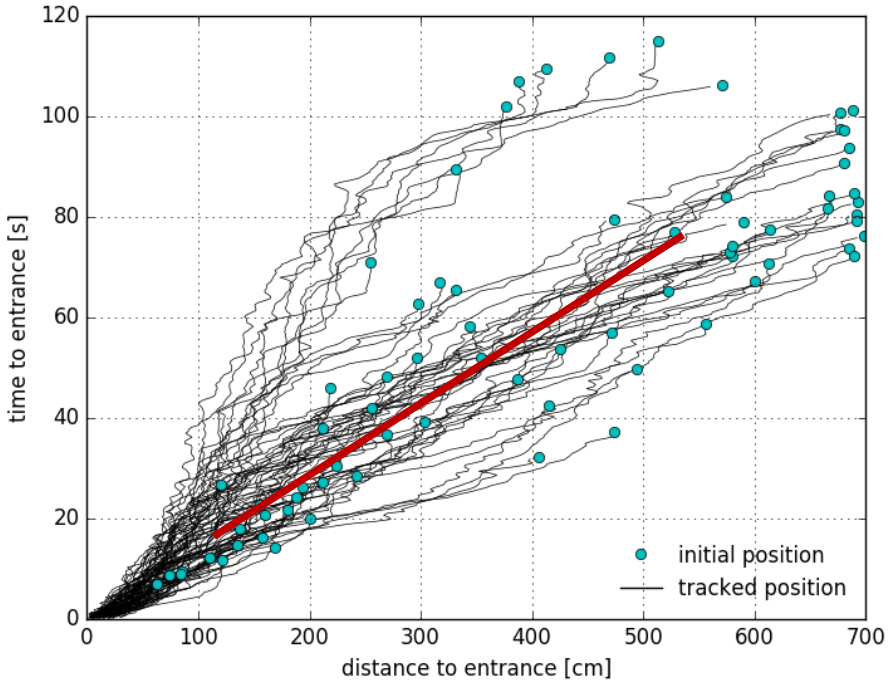
# PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

## Fairness: correlation between waiting time - distance to the entrance

Semicircle




Corridor

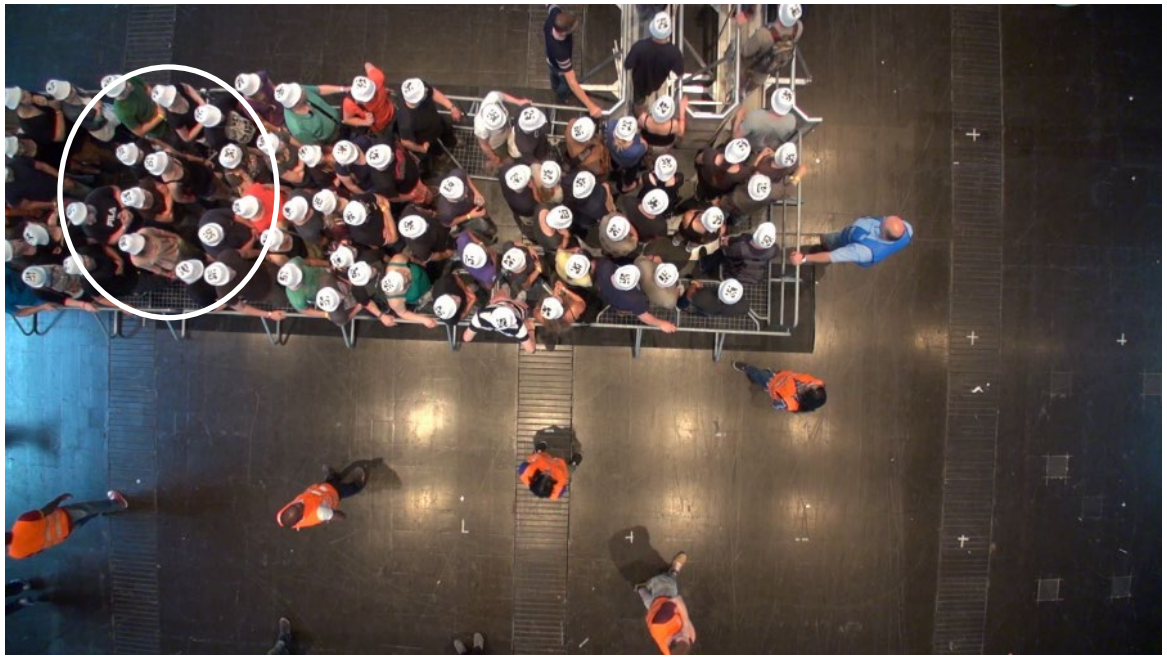



After the constriction - strong correlation in semicircle scenario!

# QUESTIONNAIRE STUDY – DESIGN

## In follow-up to the experiments (around one year later):

- Freeze frames and videos were shown to 60 students
- Instruction: Imagine to be located somewhere in the ellipses



# QUESTIONNAIRE STUDY – DESIGN

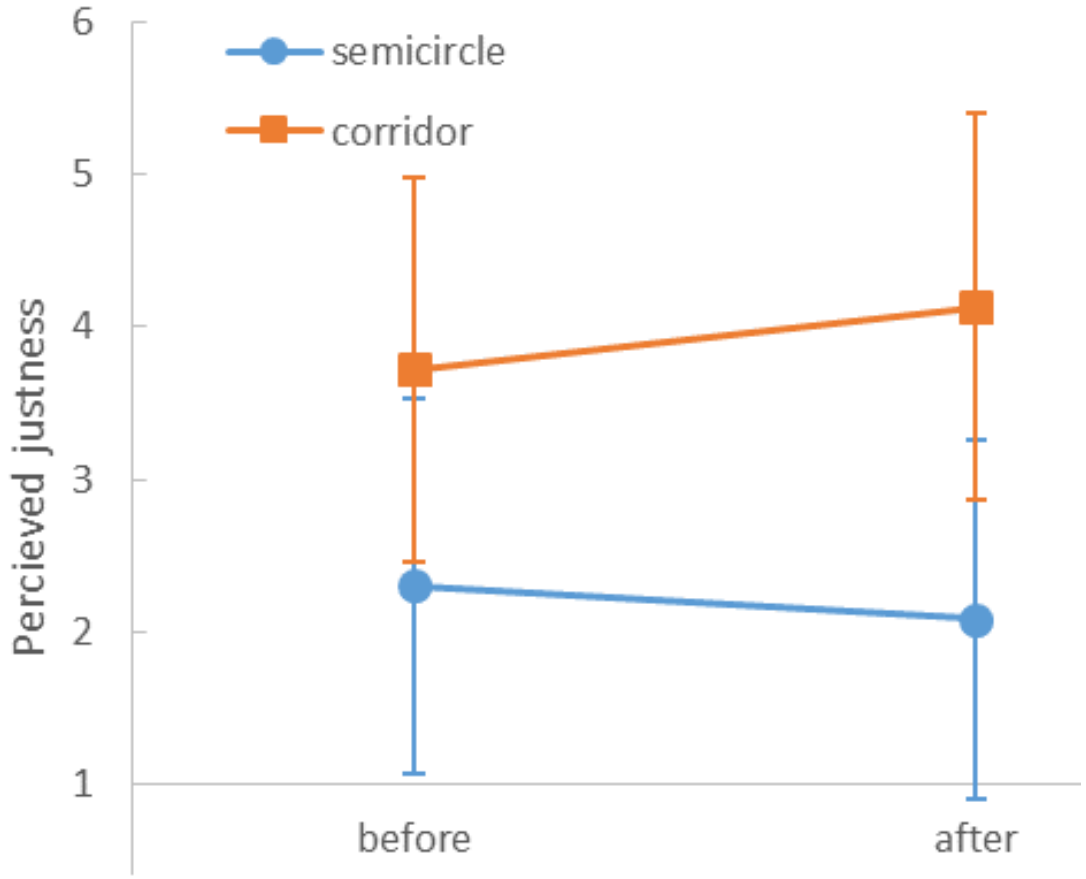
## The questionnaire (originally in German) contains four main items: fairness, progress, comfort, contribution to access faster

- How fair is this entrance procedure?
  (6-point scale, 1=very unjust, 6=very just)
- How likely is it that you will be one of the first 100 who are able to access the concert?
  (6-point scale, 1=very unlikely, 6=very likely)
- How comfortable do you feel?
  (6-point scale, 1=very uncomfortable, 6=very comfortable),
- Can you contribute to accessing the concert faster?
  (yes/no)
  and in addition strategies for being faster were requested
  (open-ended question),
- Which rules apply? (open-ended question)

# QUESTIONNAIRE STUDY – DESIGN

## Question: Perceived justness/fairness (scale 1 to 6)

- The correlation of distance to the exit and waiting time the corridor is stronger for the semicircle
- BUT the corridor is perceived as more fair



# QUESTIONNAIRE STUDY – DESIGN

## Questions: Forms of inappropriate behavior

| Semicircle | Corridor |
|---|---|
| • pushing and shoving (35) | • pushing and shoving (16) |
| • pushing someone aside (11) | • slightly pushing and shoving (4) |
| • jostling (9) | • jostling (3) |

## Question: Strategies to contribute for faster access

| Semicircle | Corridor |
|---|---|
| • pushing and shoving (25) | • pushing and shoving (21) |
| • using and filling gaps (10) | • staying on the left hand side (11) |
| • using elbows/arms/shoulders (9) | • using and filling gaps (4) |

# Density in front of the bottleneck - Experiment II

Juliane Adrian, A. Seyfried, Anna Sieben,
Crowds in front of bottlenecks at entrances from the perspective of physics and social psychology,
Interface 17(165), 20190871, 2020

# PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

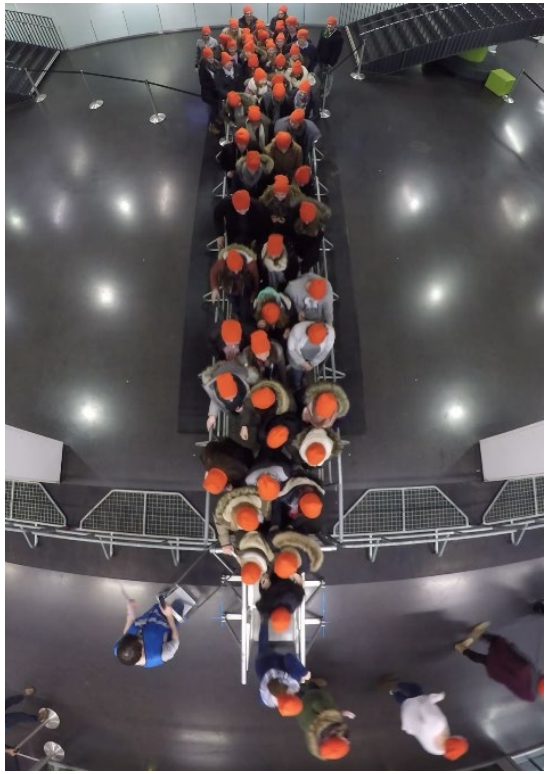
## Question

- When do participants queue and when do they start pushing?

## Influence of corridor width and motivation on

- density and waiting time
- speed
- Queuing or pushing

Experiments performed January 2017 at the University of Wuppertal with students (between two lectures)



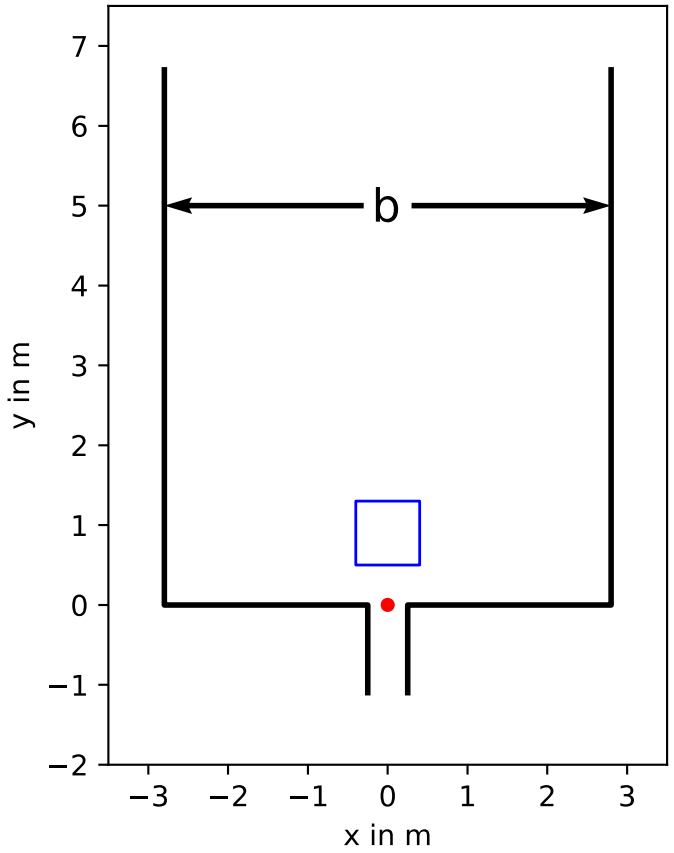
Juliane Adrian, A. Seyfried, Anna Sieben, Crowds in front of bottlenecks at entrances from the perspective of physics and social psychology, Interface 17(165), 20190871, 2020

# PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

## Setup of the boundaries and variations

| | | | | | |
|---|---|---|---|---|---|
| ***b*** | 1.2 m | 2.3 m | 3.4 m | 4.5 m | 5.6 m |
| ***N*** | 11, 24, 25, 63 | 20, 42 | 22, 67 | 42, 42 | 57, 75 |
| ***h*** | hi, lo | hi, lo | hi, lo | hi, lo | hi, lo |

- **b:** corridor width
- **N**: number of participants
- **h**: degree of motivation



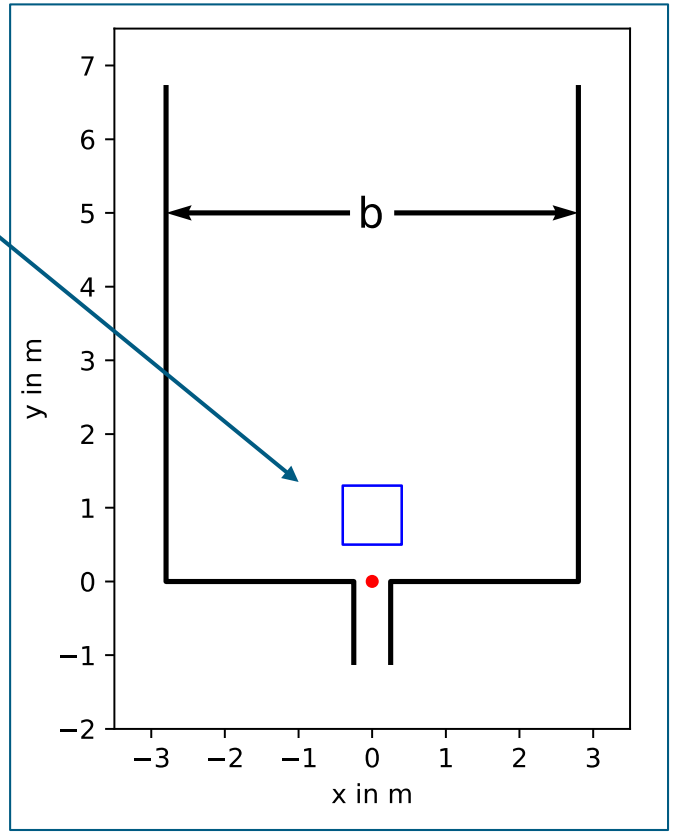

## Motivation

- Scenario: entrance to the concert of a favorite artist
- High Motivation: only the first of the audience will have an undisturbed view of the stage
- Low Motivation: the complete audience will have an undisturbed view of the stage

# PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

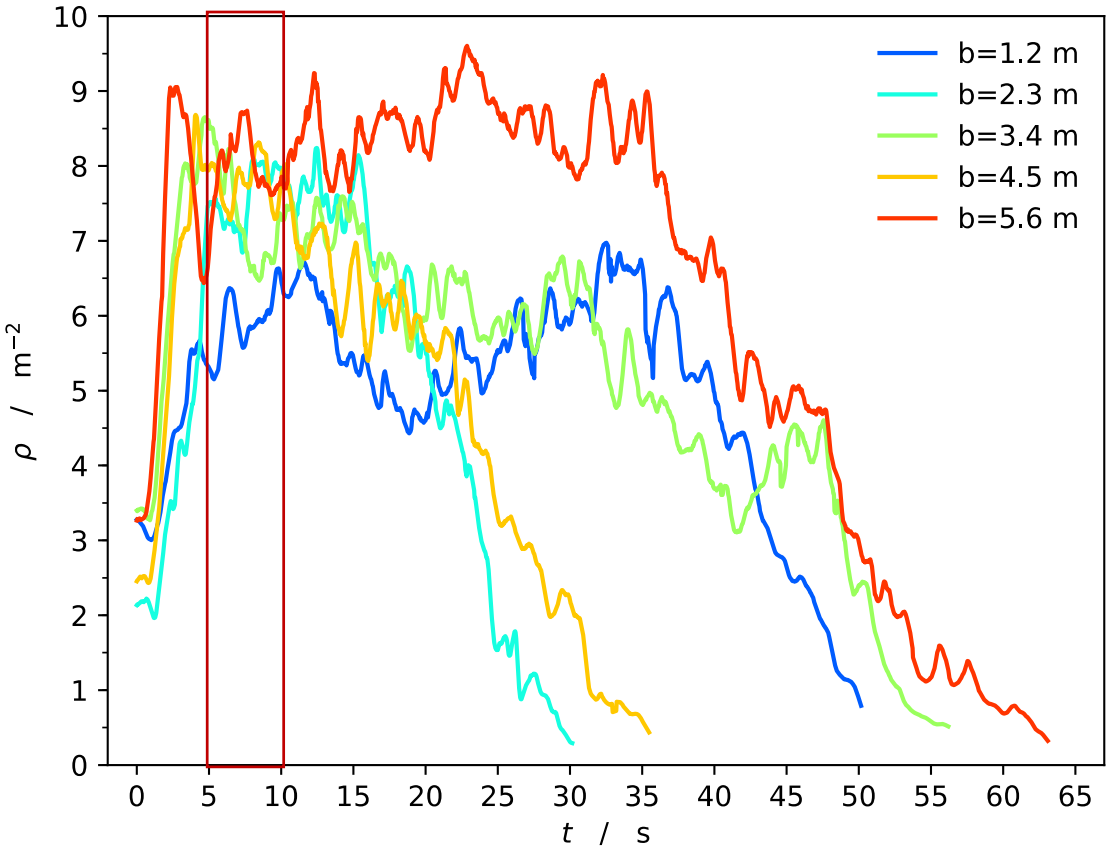
# PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

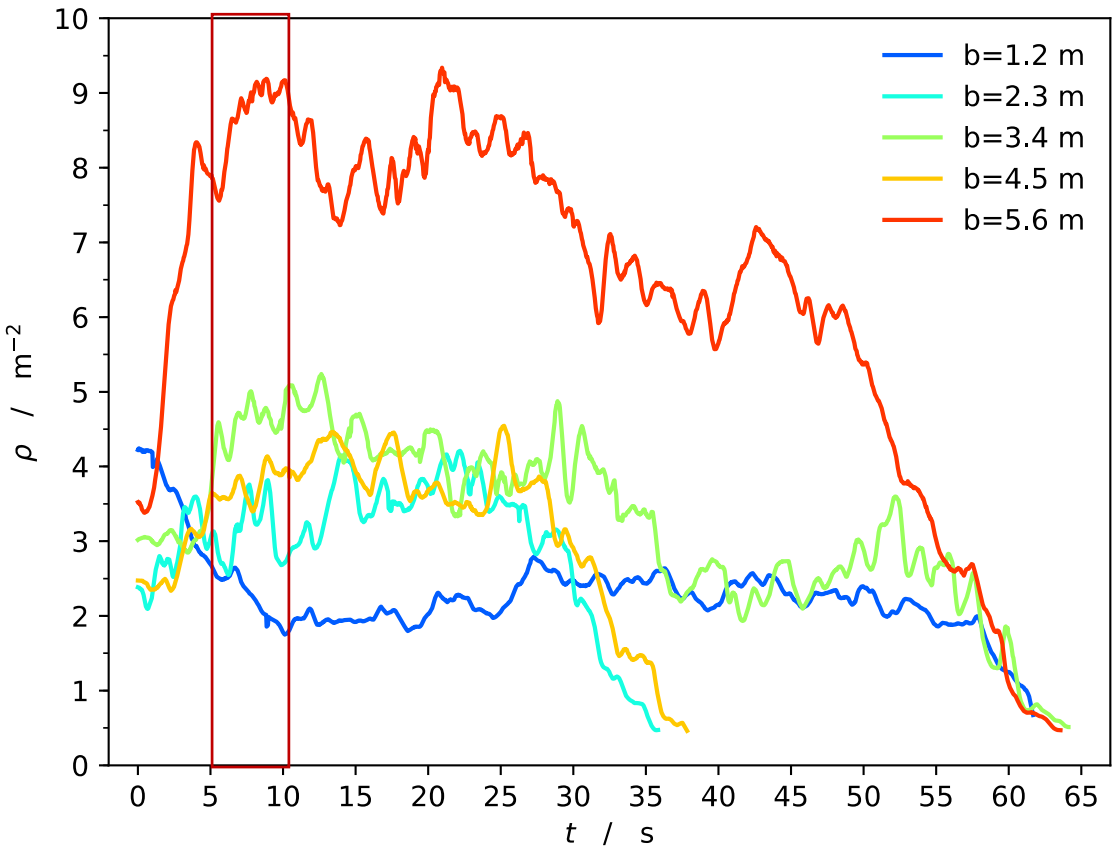
## Density within the measurement area



# PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

## Density within the measurement area

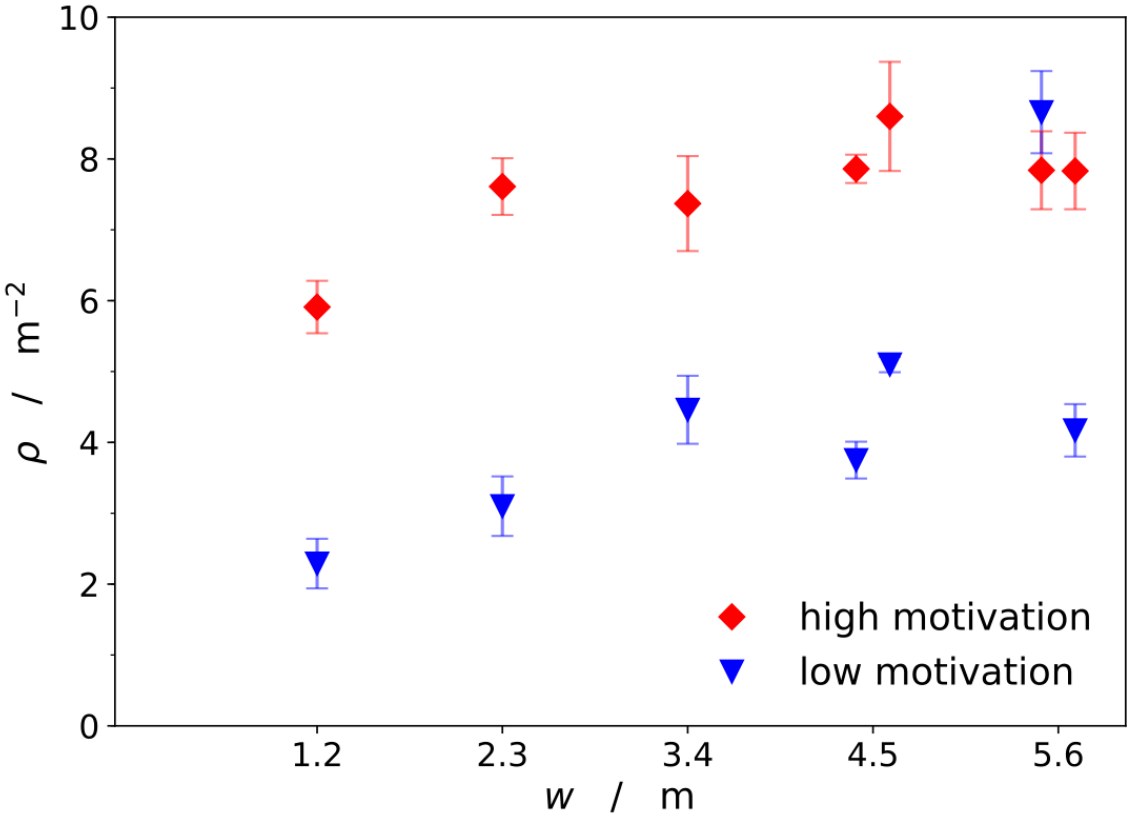


# INTRODUCTION

## Results

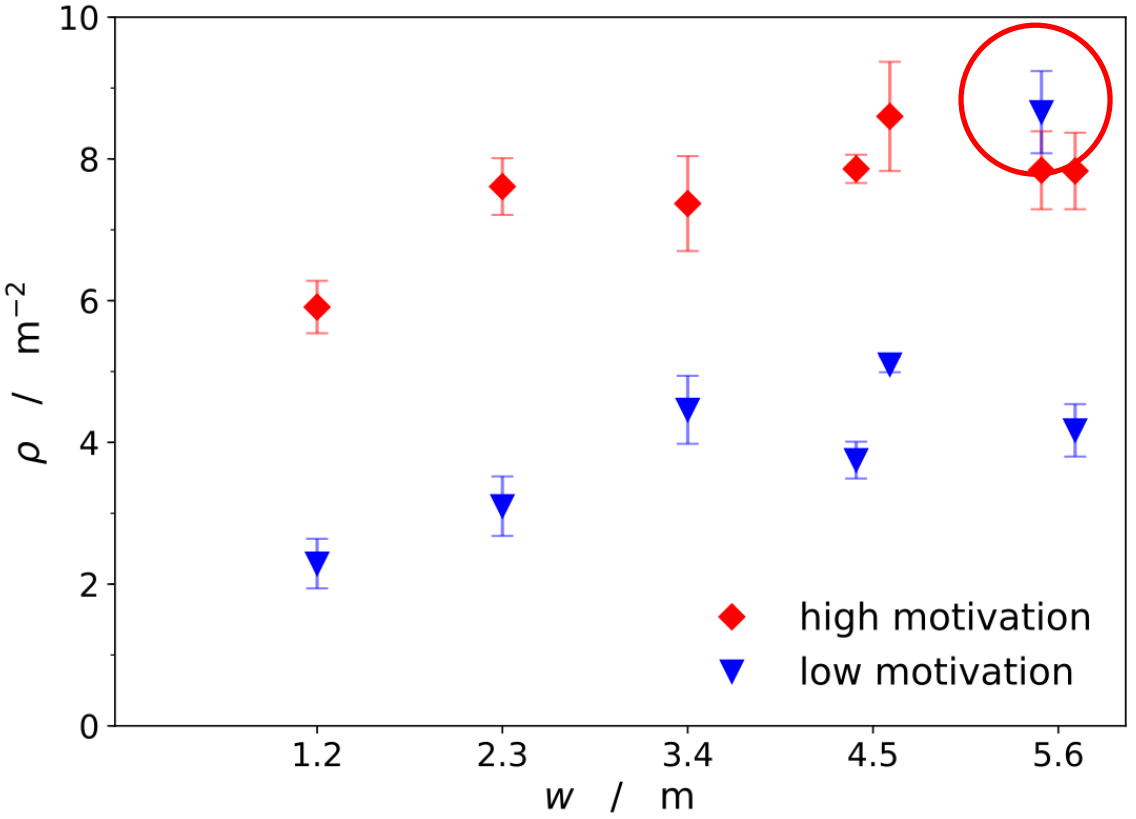
- Density increases with increasing corridor width
- 2 density-levels: dependent on degree of motivation



# INTRODUCTION

## Results

- Density increases with increasing corridor width
- 2 density-levels: dependent on degree of motivation
- At wide corridors (width = 5.6 m) and low motivation two states occur
  - one with low density
  - one with high density and pushing:

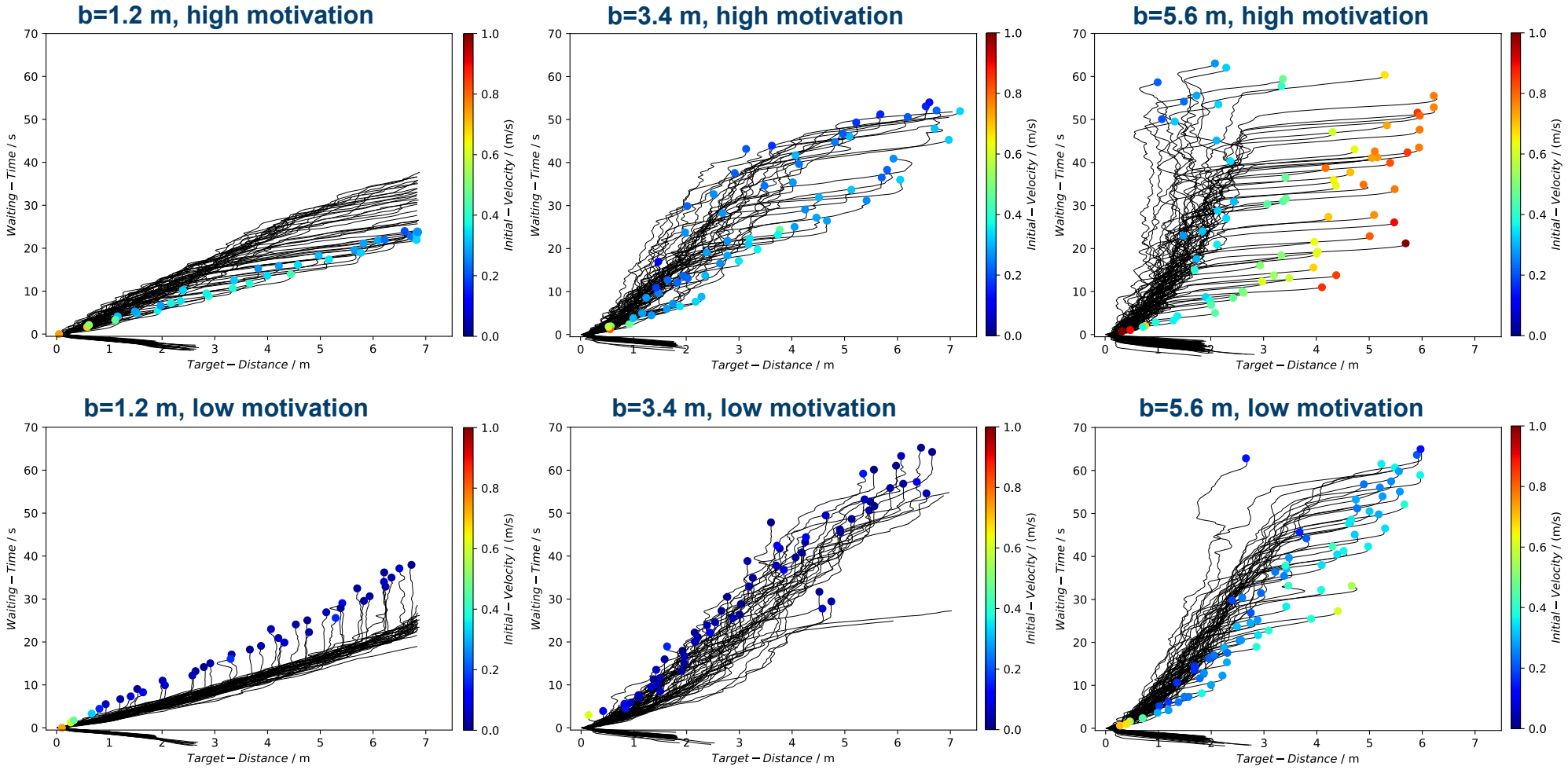


# PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

**High motivation**

**Low motivation**

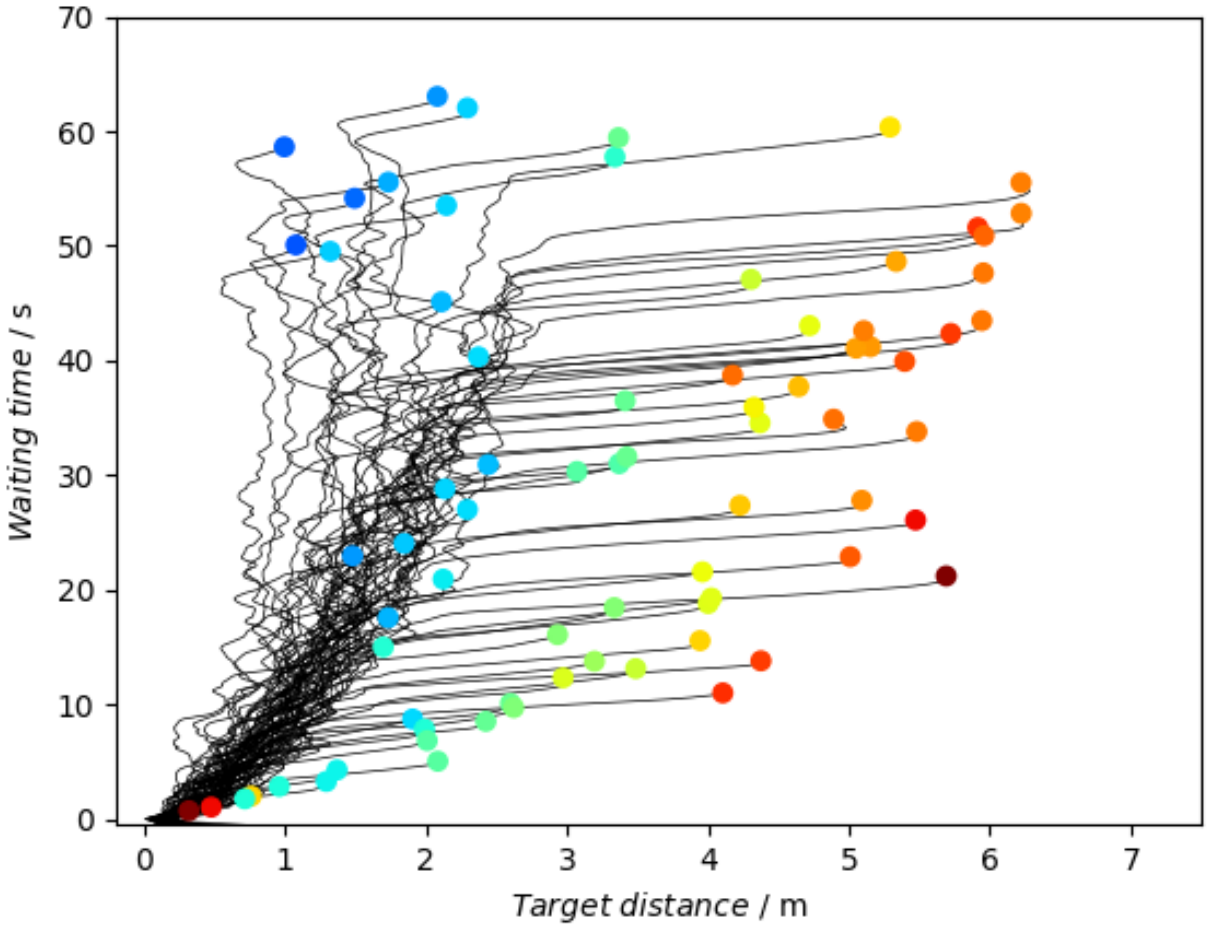
# PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II



# PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

## Results

- Not all pedestrian have the same motivation
- Yellow and red : high initial speed -> constriction
- Blue: low speed – stand still - no participation in the constriction



# SUMMARY

## Both, queuing and pushing behavior could be observed

- Pushing is indicated by
- high density
- high initial velocity

## High density is facilitated by

- increasing the corridor width
- increasing the degree of motivation (e.g. by introducing rewards)

## The results of the experiments show

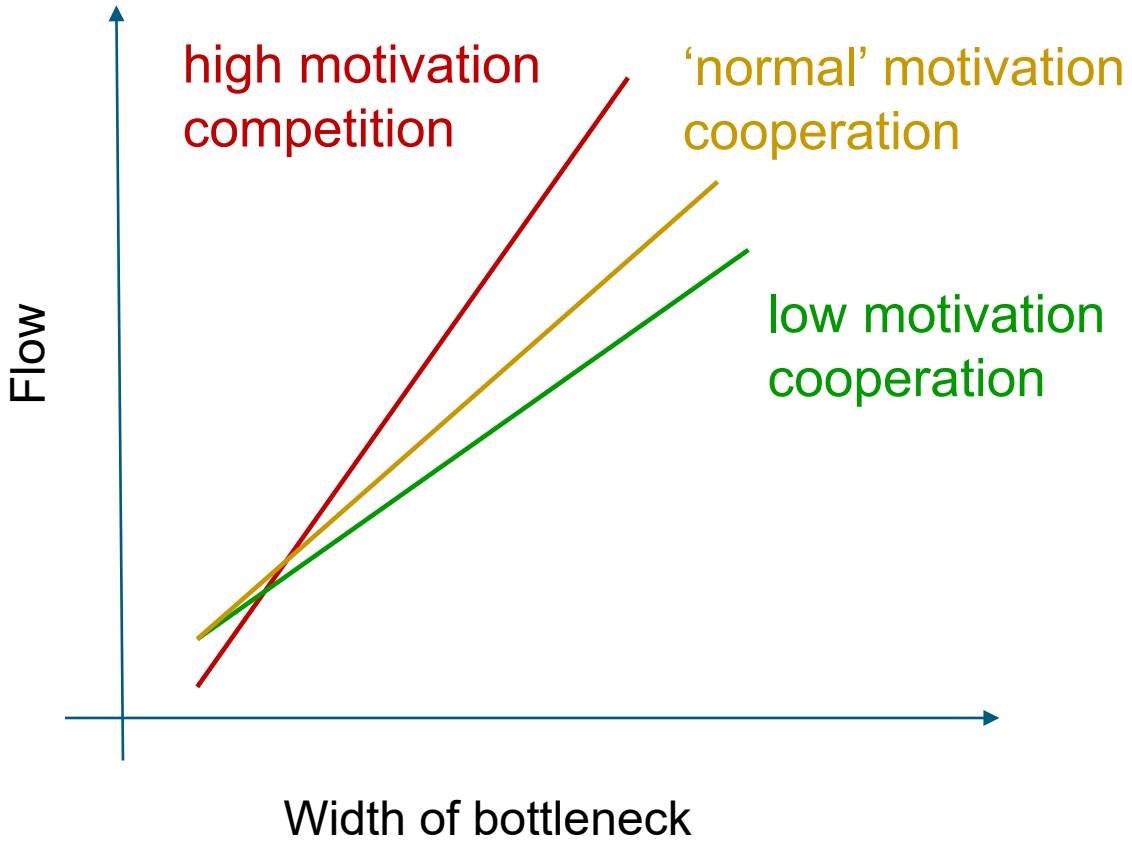
- Physical properties like the width of the corridor has an influence on the dynamics
- But also social-psychological factors, here motivation, could have a strong influence.

## Both perspectives – science and social psychology – are important to understand pedestrian dynamics!

# SUMMARY

## Capacity of a bottleneck

- Model where the capacity increases with the number of lanes (like in vehicular traffic) have no empirical evidence
- The capacity increases continuously with the width of the bottleneck
- In general a high motivation improves the flow (people move faster, fill gaps, get closer)
- High motivation and competition could increase the probability of clogs
- **A negative effect of motivation on the capacity is only evident at bottlenecks of small width (b ≈ < 1 m) and in competitive settings.**



# OUTLOOK

Source: Marc Strunz-Michels

# OUTLOOK

## Open data repository, software and journal

- http://ped.fz-juelich.de/da
- https://www.jupedsim.org/index.html
- https://collective-dynamics.eu