PEDESTRIAN BOTTLENECKS – CONGESTION DYNAMICS AND PUSHING

SEPT 13th, 2022 WORKSHOP USTC INVITED BY JUN ZHANG

OVERVIEW

Introduction

- Congestion, capacity, motivation, competition and clogging

Bottleneck capacity / flow

- Influence of width
- Influence of motivation

Density in front of the bottleneck

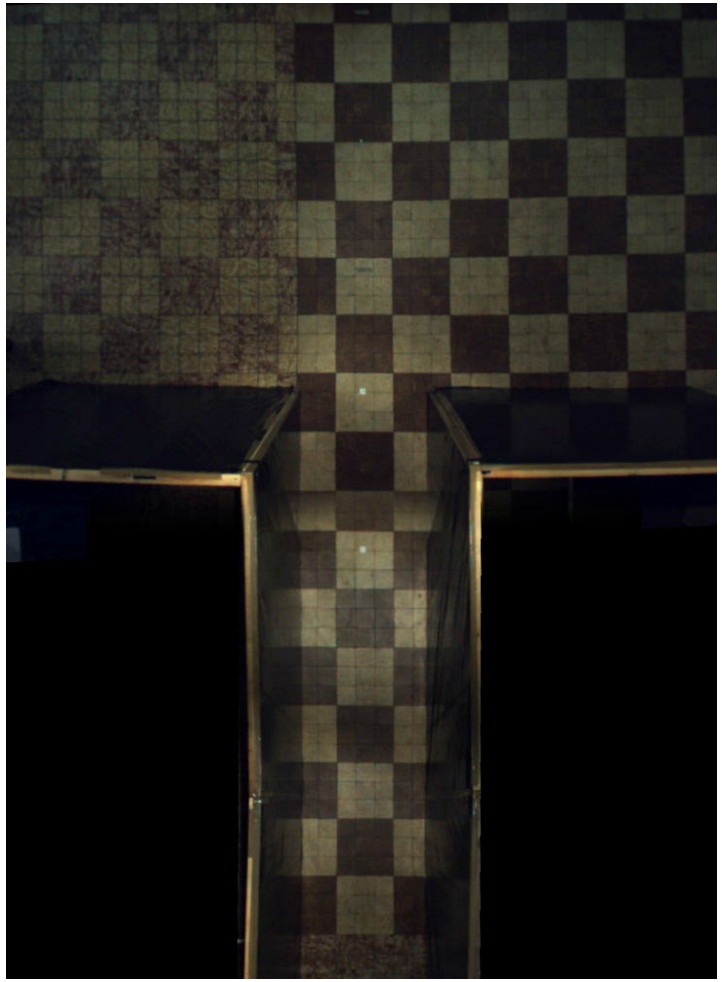
- Experiment I: Social norms and fairness
- Experiment II: Science and social psychology

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



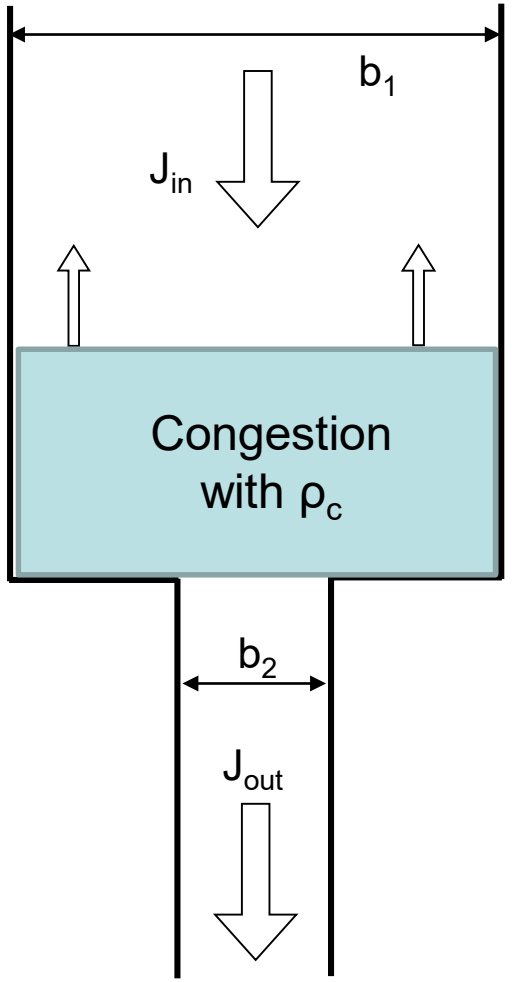
INTRODUCTION

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 ρ_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*

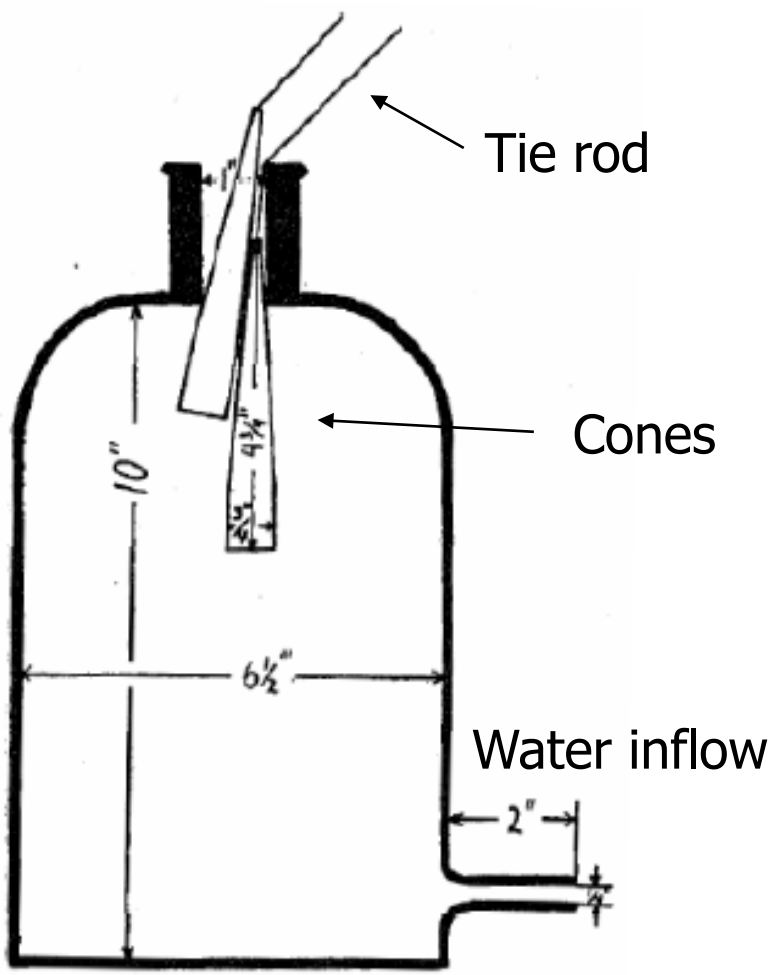
- Groups of 15-21 students
- Task: Pulling out cones dry
- Only one cone at a time - otherwise clogging

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

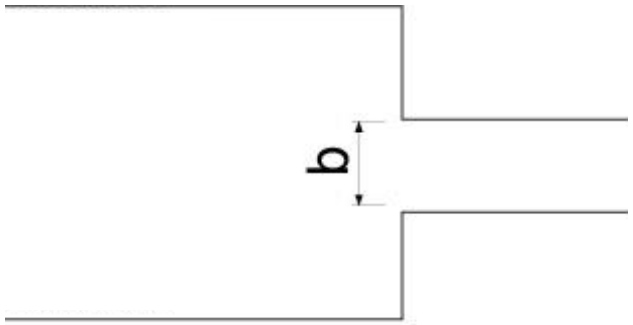
1. Influence of
   - spatial structure of the boundaries
   - motivation (triggered by incentives / rewards)

   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)

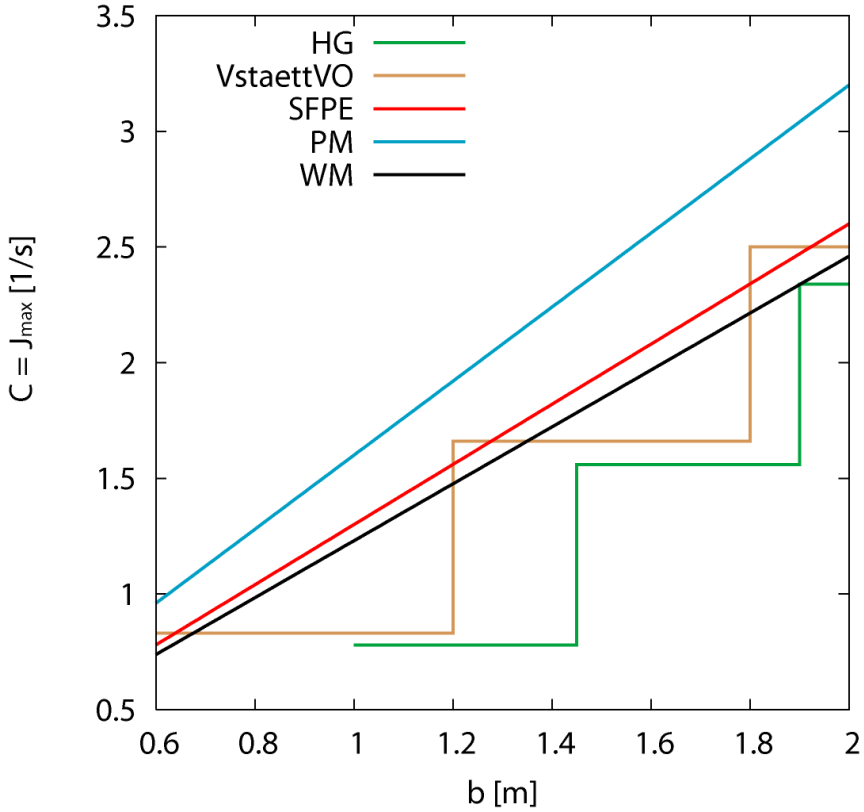
- Formation of lanes
- Lane distances independent of b

→ C increases stepwise

SFPE, WM, PM

- C_s = C/b independent of b

→ C increases linearly

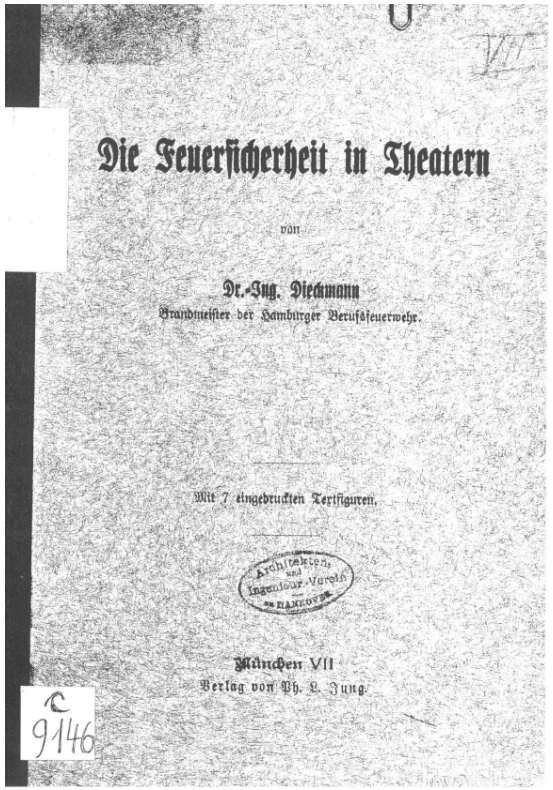


SFPE: P. J. DiNenno (1995)
PM: V. M. Predtechenskii et al. (1978)
WM: U. Weidmann (1993)
HG: S.P.Hoogendoorn et al. (2005)
VstättVO: ARGEBAU

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.

Architekten- und Ingenieur-Verein zu Hannover

München VII

Verlag von Ph. C. Jung

9146

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.

Library of Congress
SEP 22 1933
Smithsonian Deposit

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

EXPERIMENT

Bottleneck flow*,**

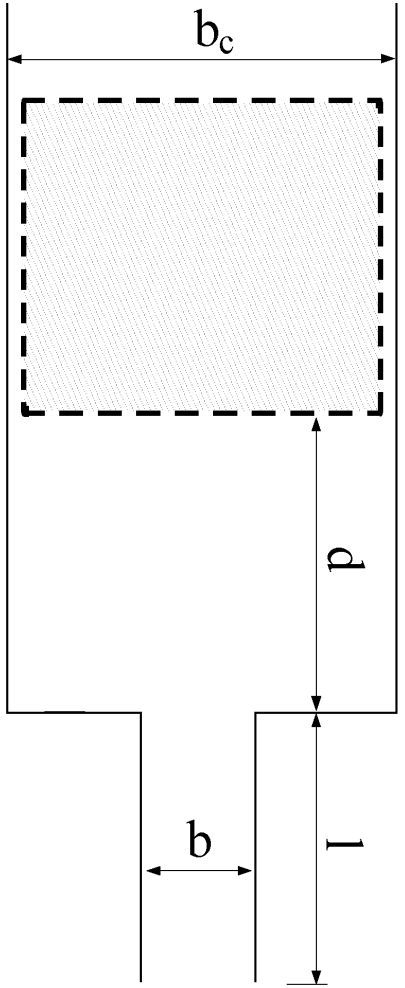
- Bottleneck width b

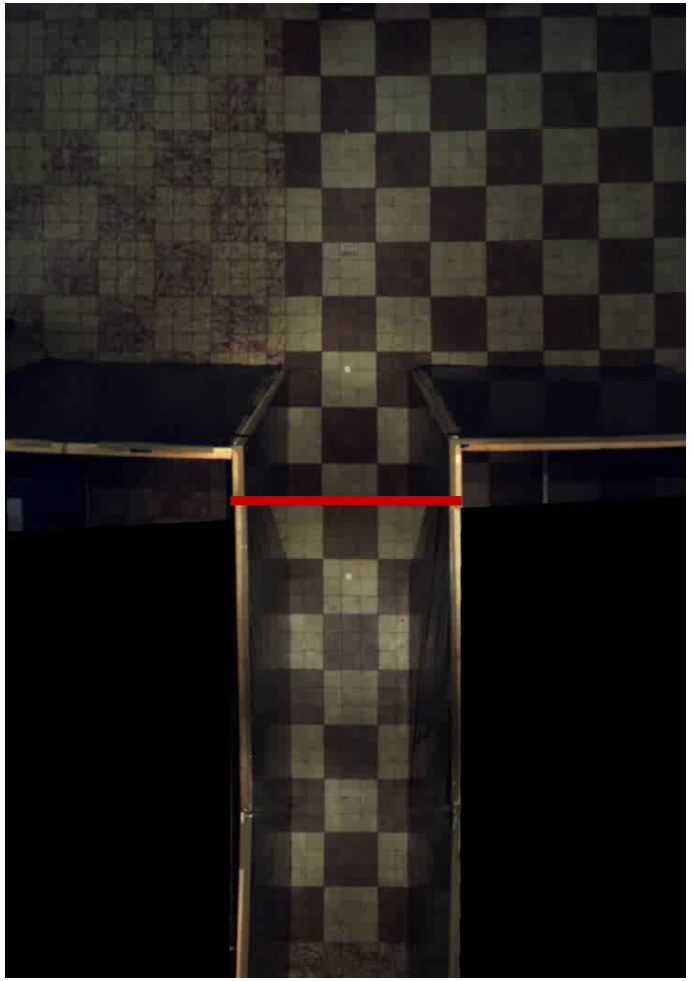
  0.8, 0.9, 1.0, 1.1, …, 2.5 m

- Bottleneck length l

  0.1, 2.0, 4.0 m

- Corridor width b_C
- …

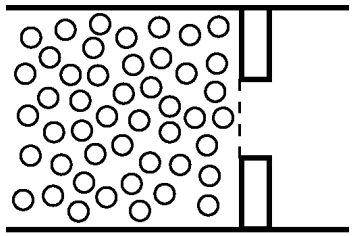




*Seyfried, A. et al. New insights into pedestrian flow through bottlenecks Transportation Science, 2009, 43, 395-406

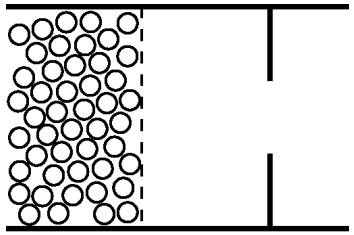
**Liddle, J. et al. Microscopic insights into pedestrian motion through a bottleneck, resolving spatial and temporal variations ArXiv, 2011

CAPACITY OF A BOTTLENECK: C(b)



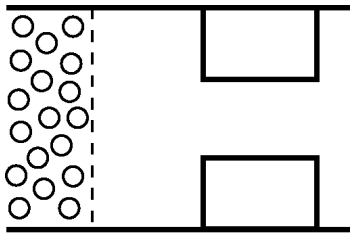
Kretz et al.

J. Stat. Mech., P10014 (2006)



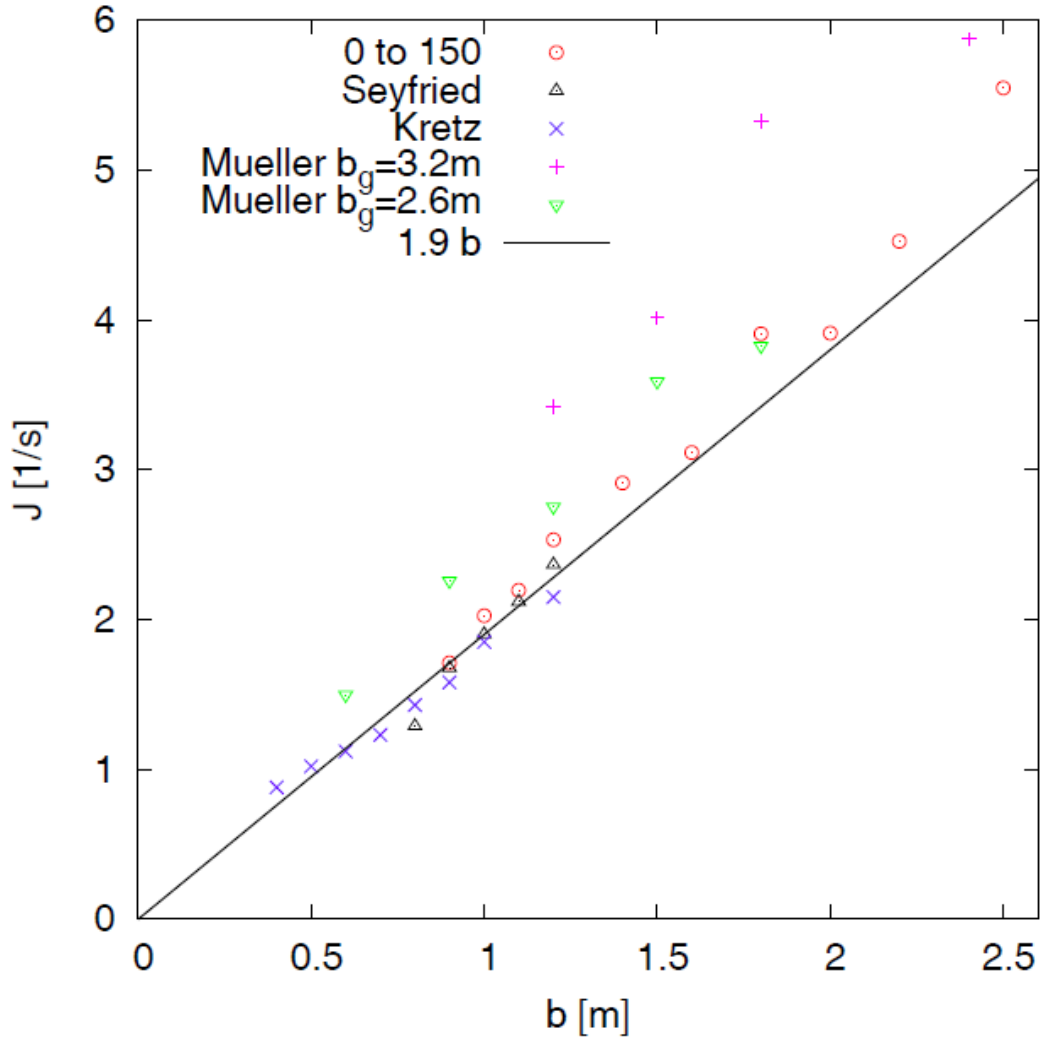
Mueller K.

Dissertation, Magdeburg (1981)



Seyfried et al.

Trans. Sci., 43, 395-406 (2009), …



Bottleneck flow – influence of motivation

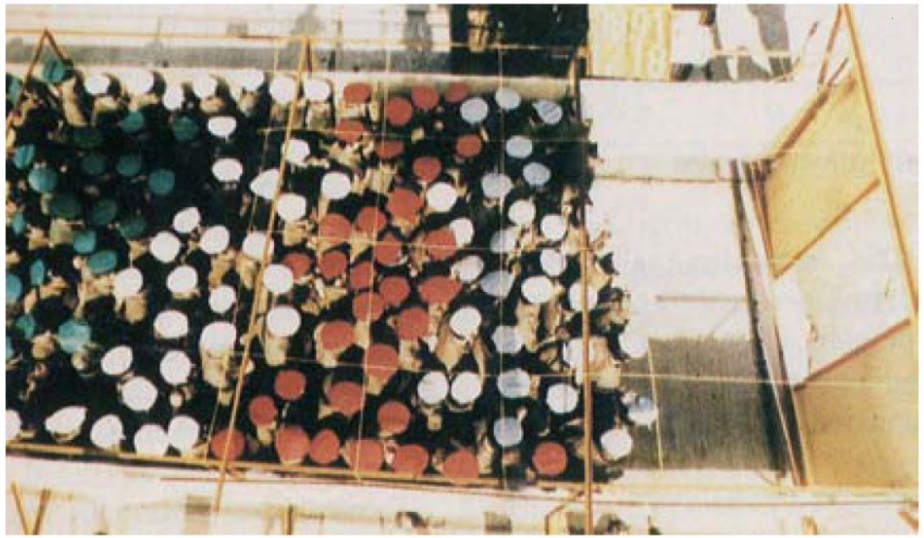
EXPERIMENTS MÜLLER, 1981*

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*

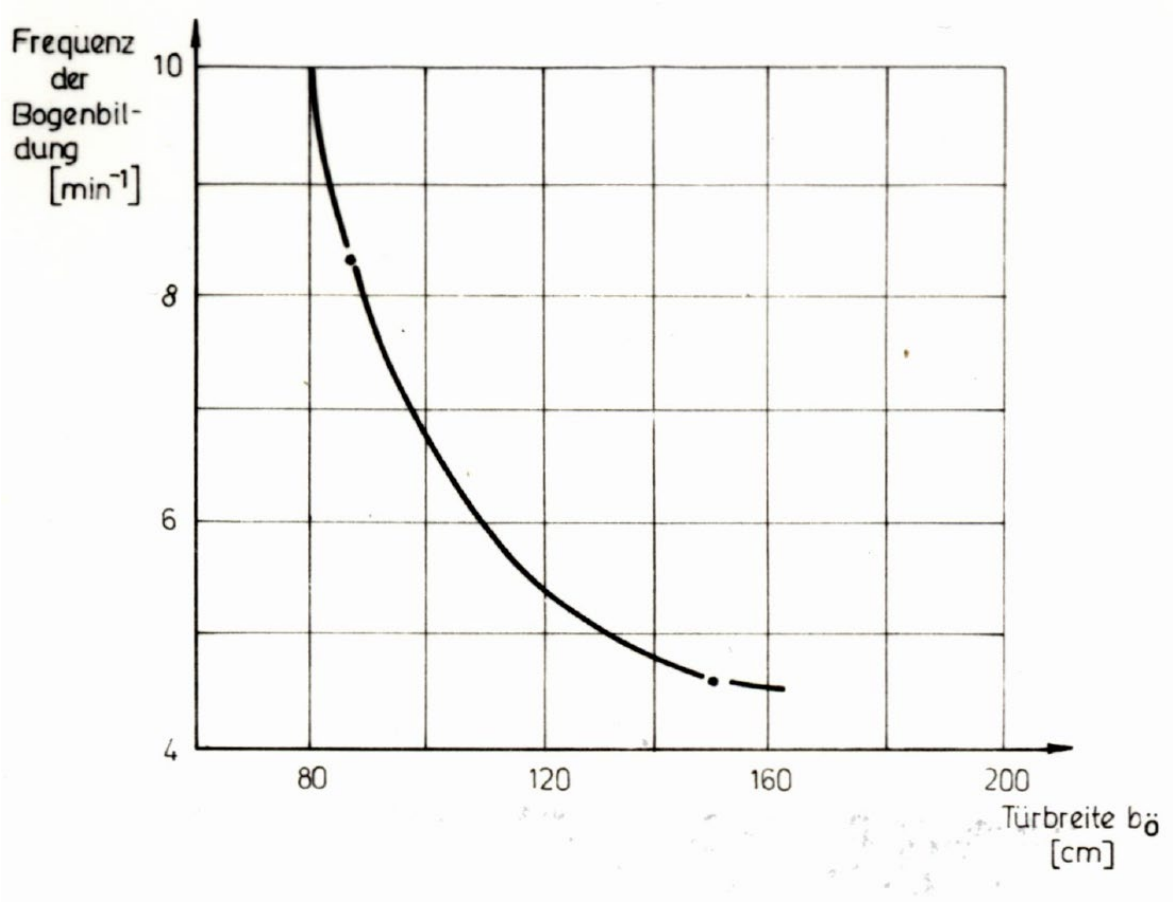
The frequency of clogs appearing at competitive settings depend on the width of the bottleneck

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!



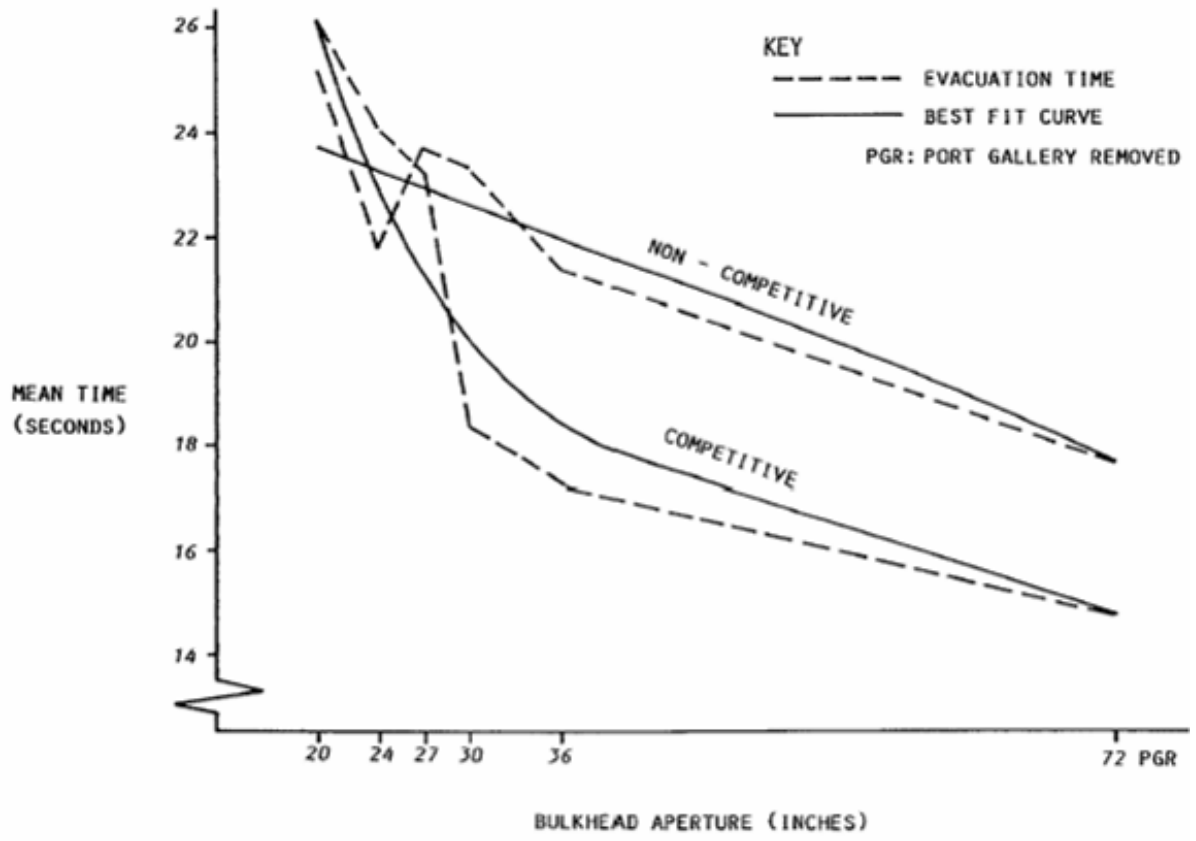
EXPERIMENTS MUIR ET AL. 1996*

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)

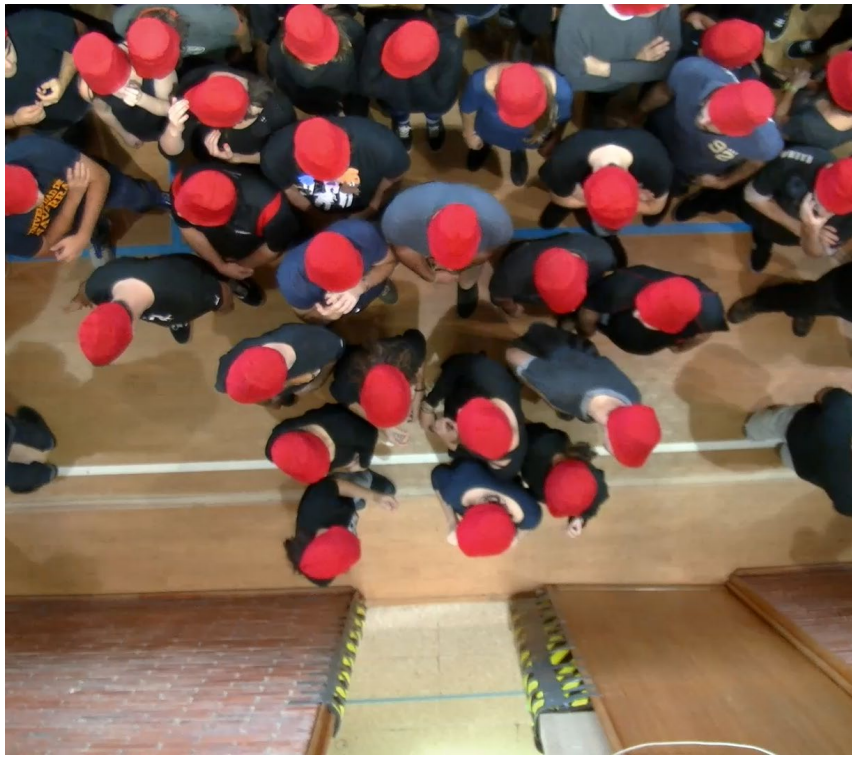
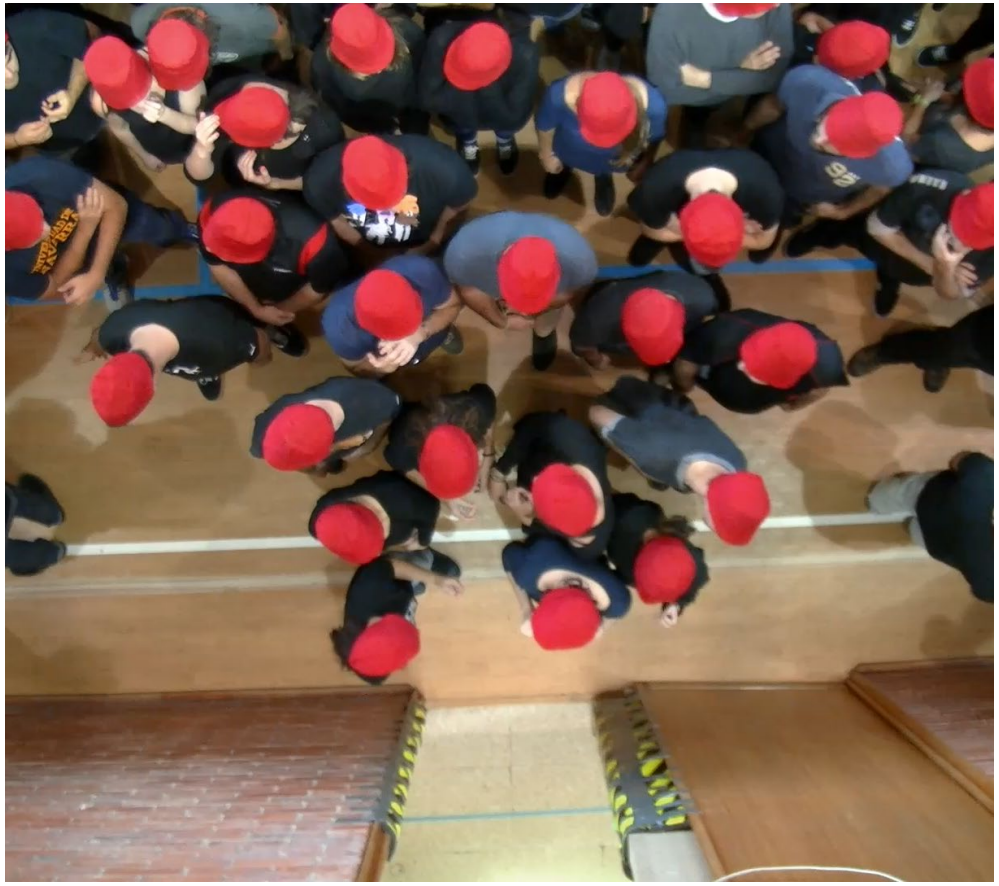


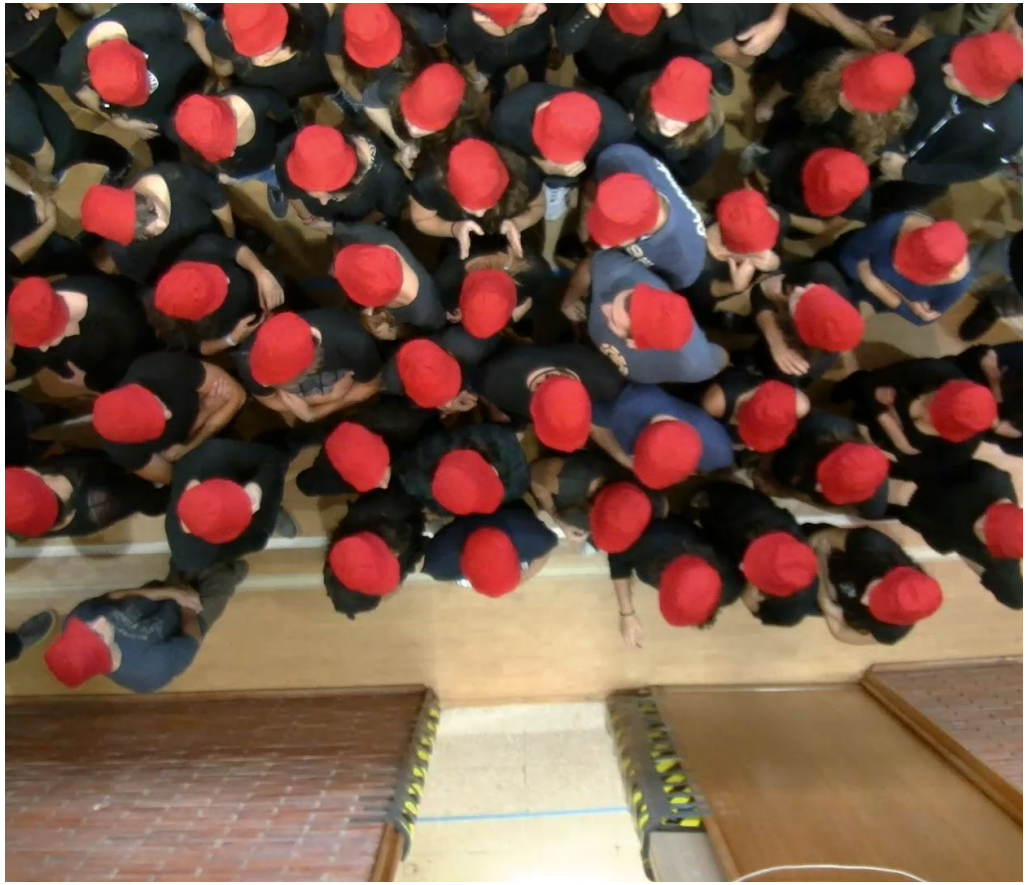
Table 1. Number of runs and passage times for each experimental situation.

	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*





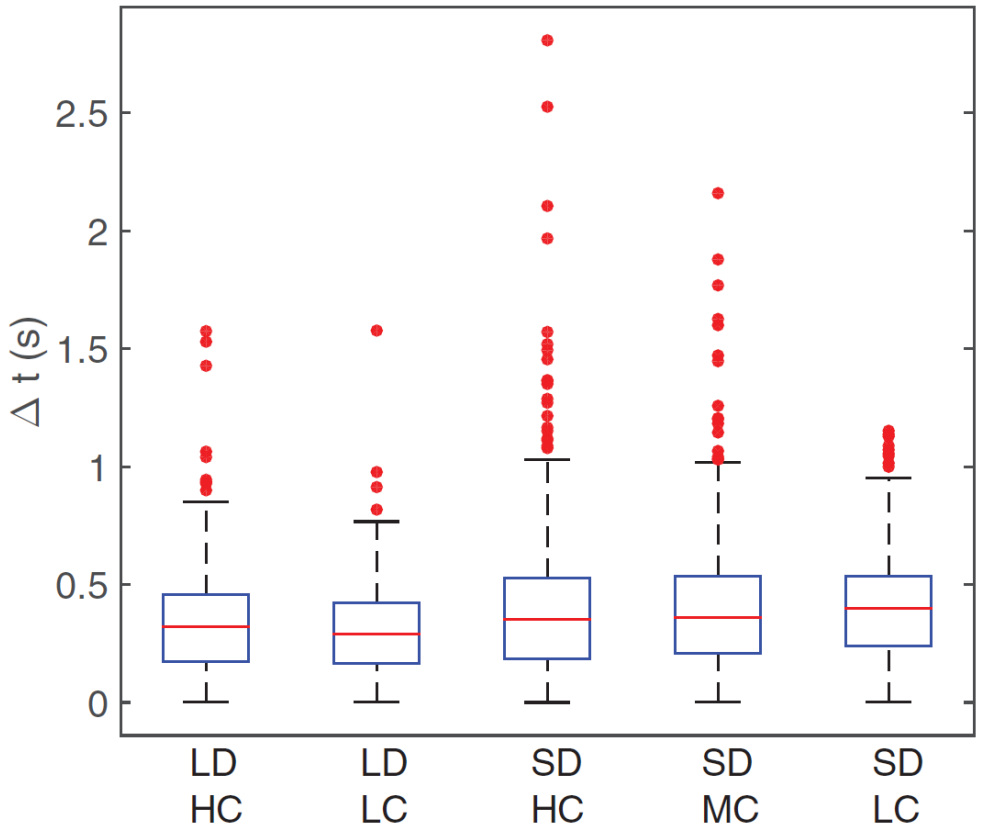
*Garcimartín, Parisi, Pastor, Martín-Gómez, Zuriguel, Flow of pedestrians through narrow doors with different competitiveness, J. Stat. Mech, 043402, 2016

EXPERIMENTS GARCIMATIN ET AL. 2016*

- The probability of clogs increases leading to extreme events with large interruptions of the flow Δt

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

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

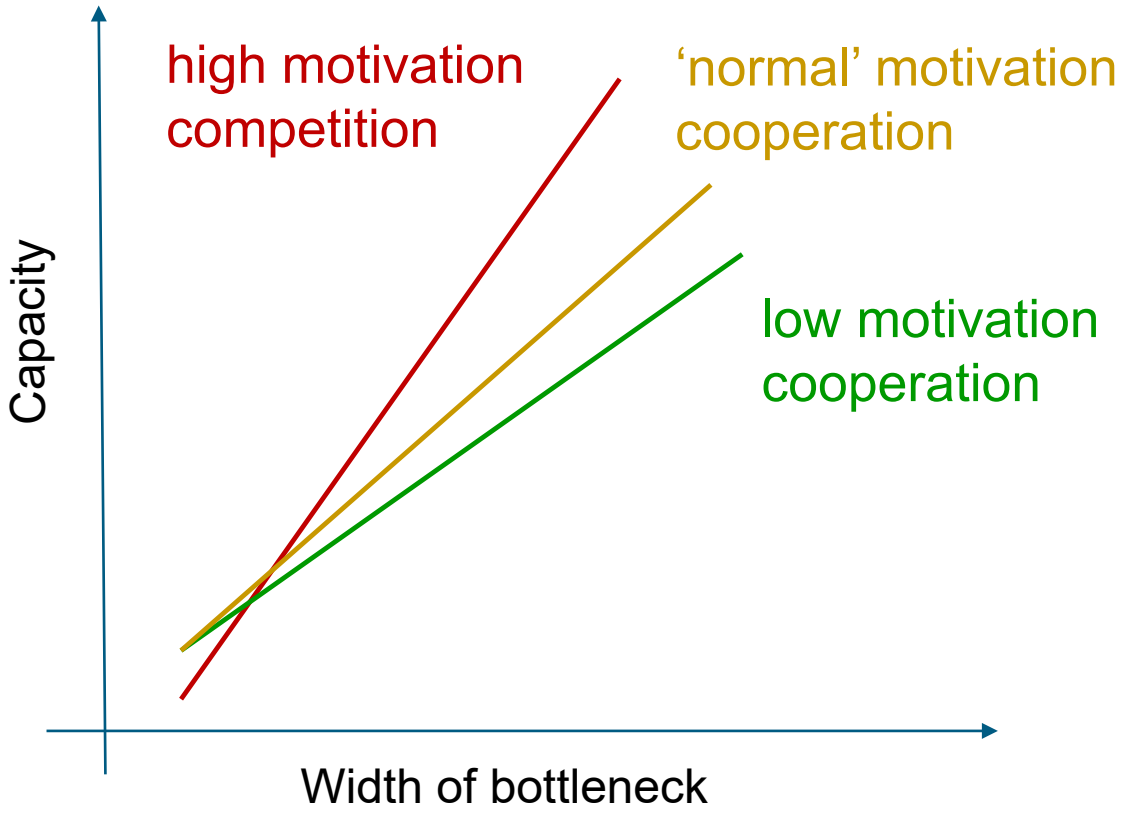


*Garcimartín, Parisi, Pastor, Martín-Gómez, Zuriguel, Flow of pedestrians through narrow doors with different competitiveness, J. Stat. Mech, 043402, 2016

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

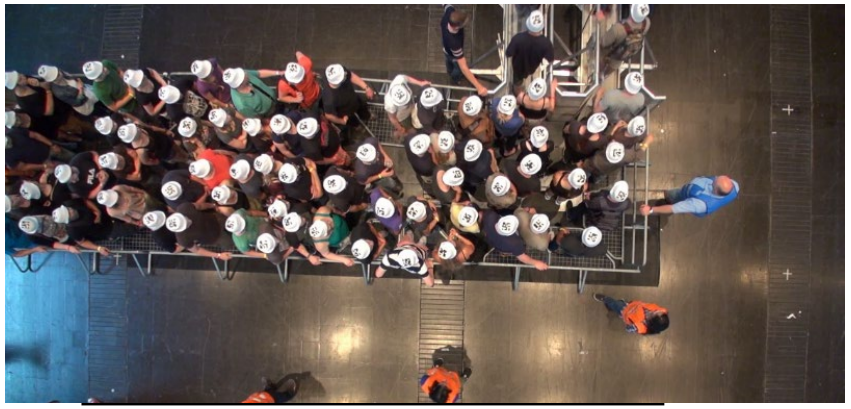
PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

Spatial structure of the barriers

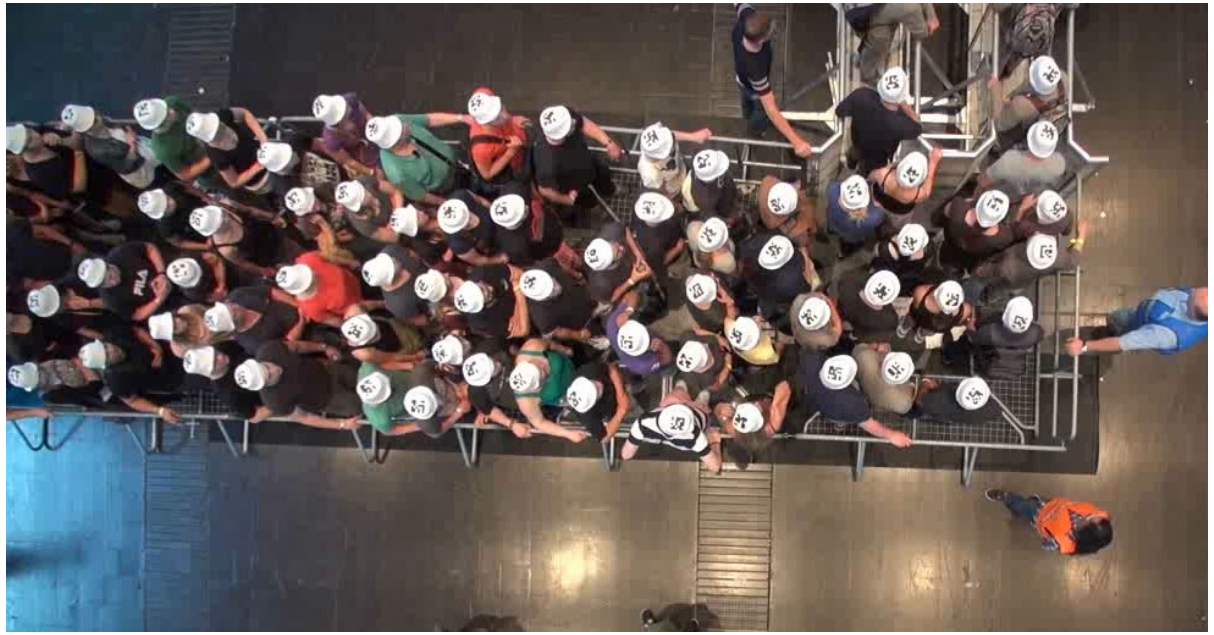
- Simple barrier with entrances,
  Test persons form a semicircle
- Corridor leading to the entrances

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..."

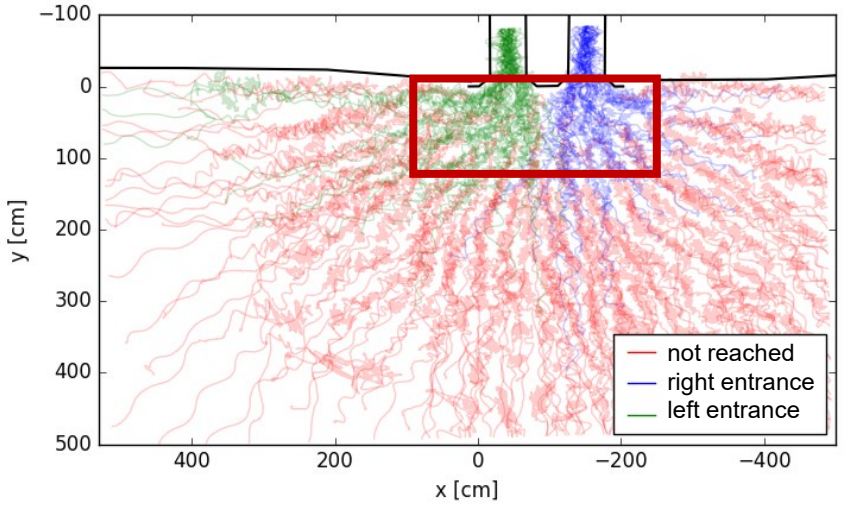


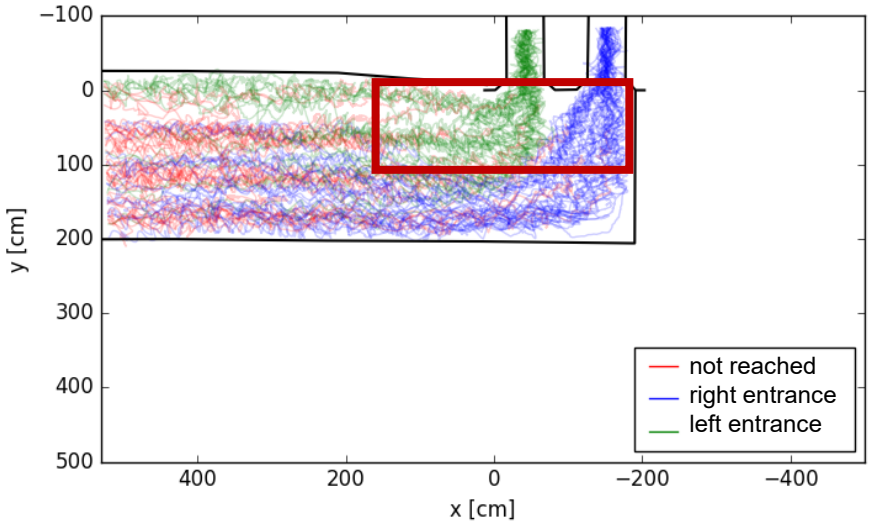
PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

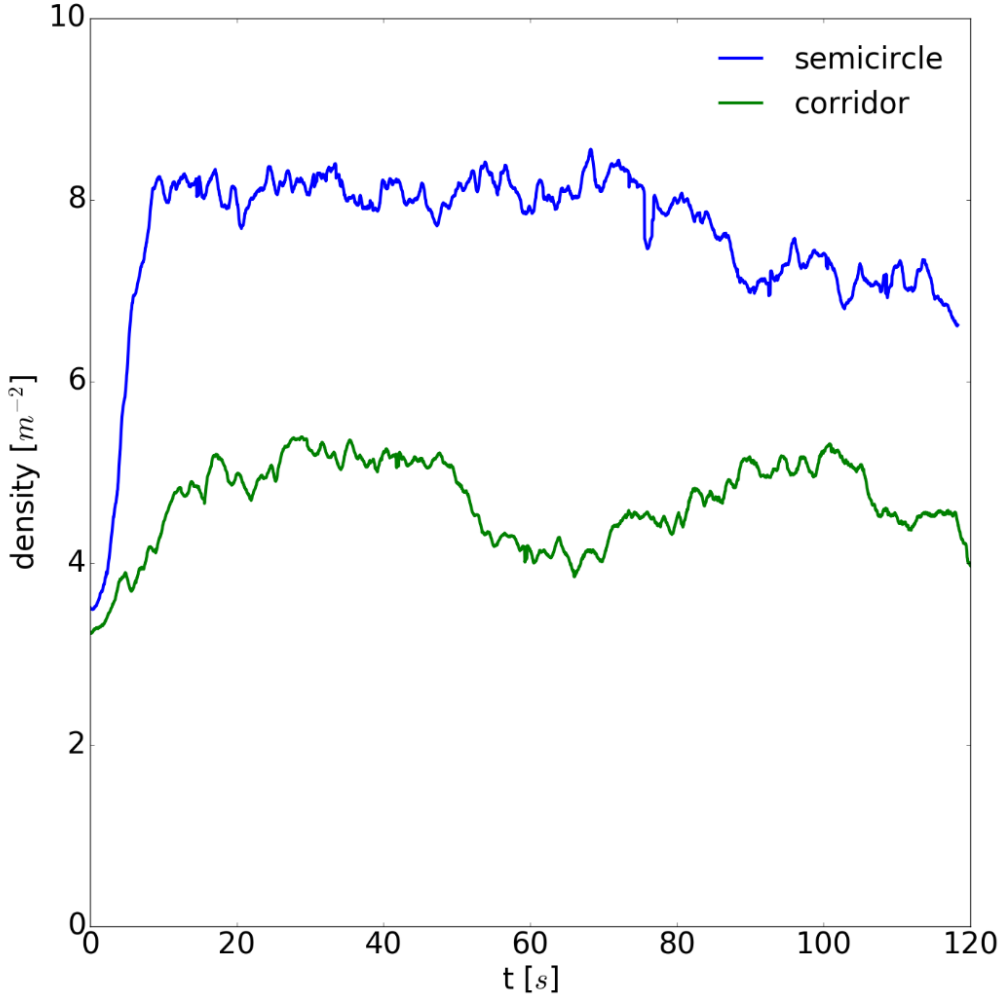


PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

Trajectories and time series of the densities



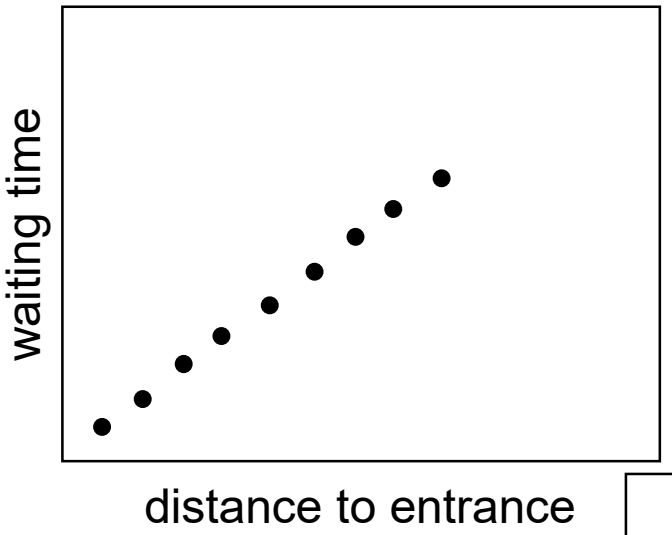


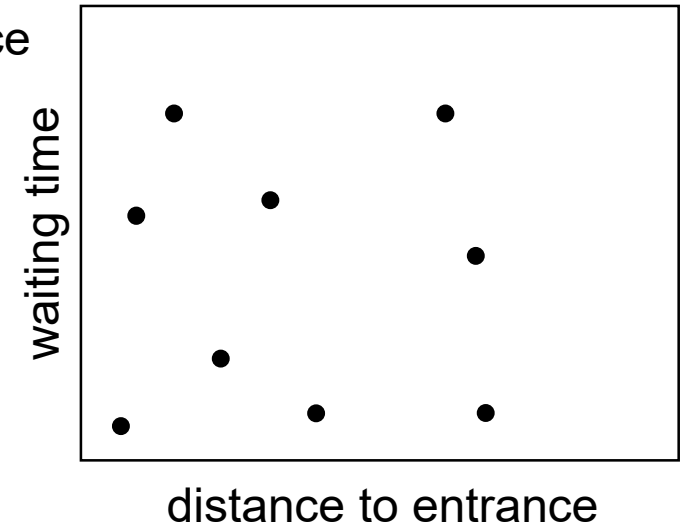


PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

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

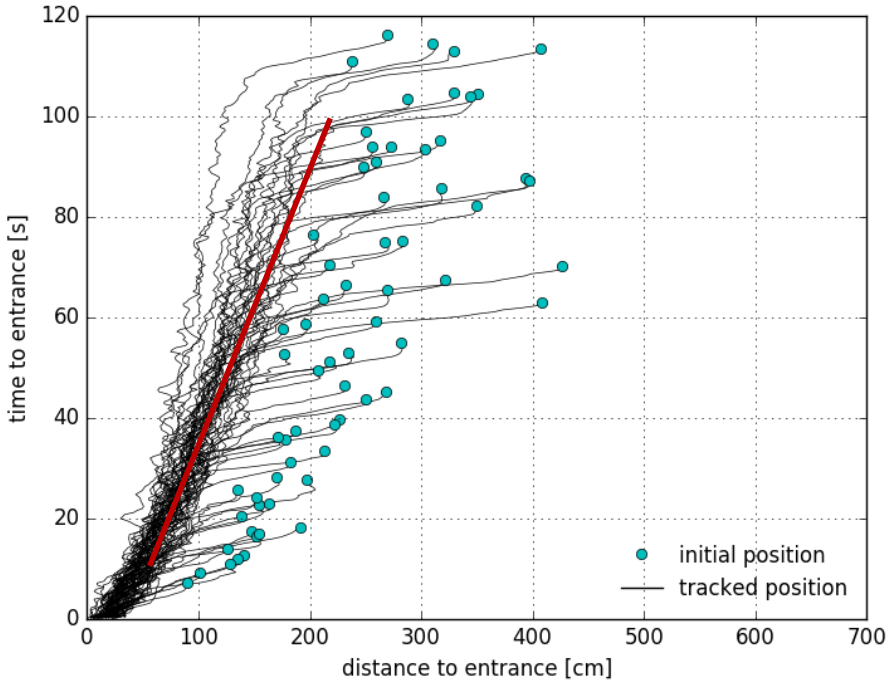




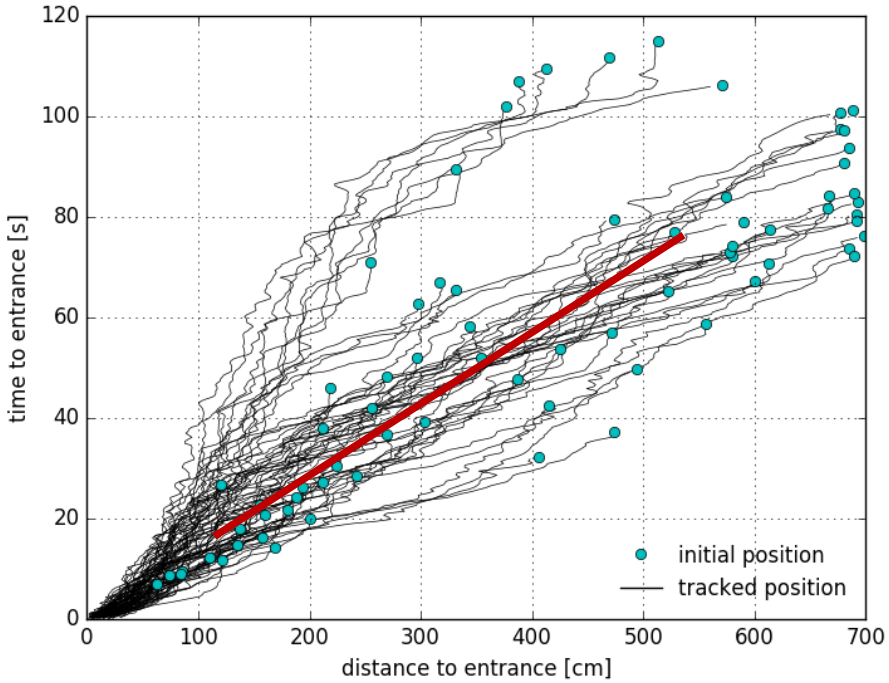
PHYSICS AND SOCIAL-PSYCHOLOGY - EXPERIMENT I

Fairness: correlation between waiting time - distance to the entrance

Semicircle



Corridor

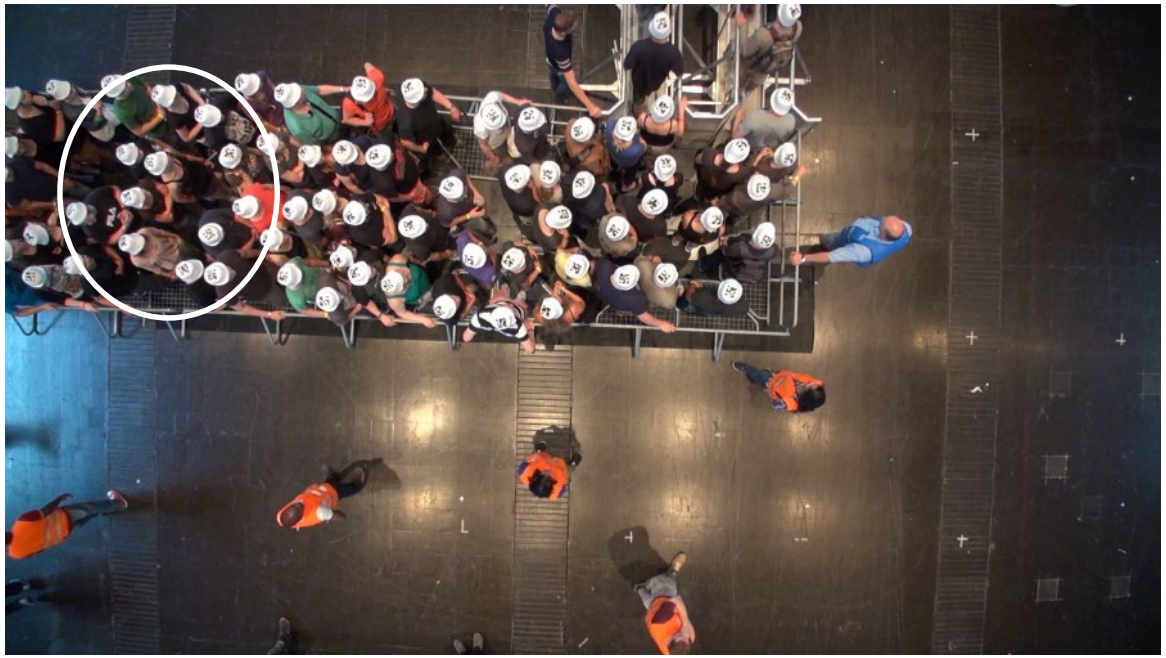


After the constriction - strong correlation in semicircle scenario!

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

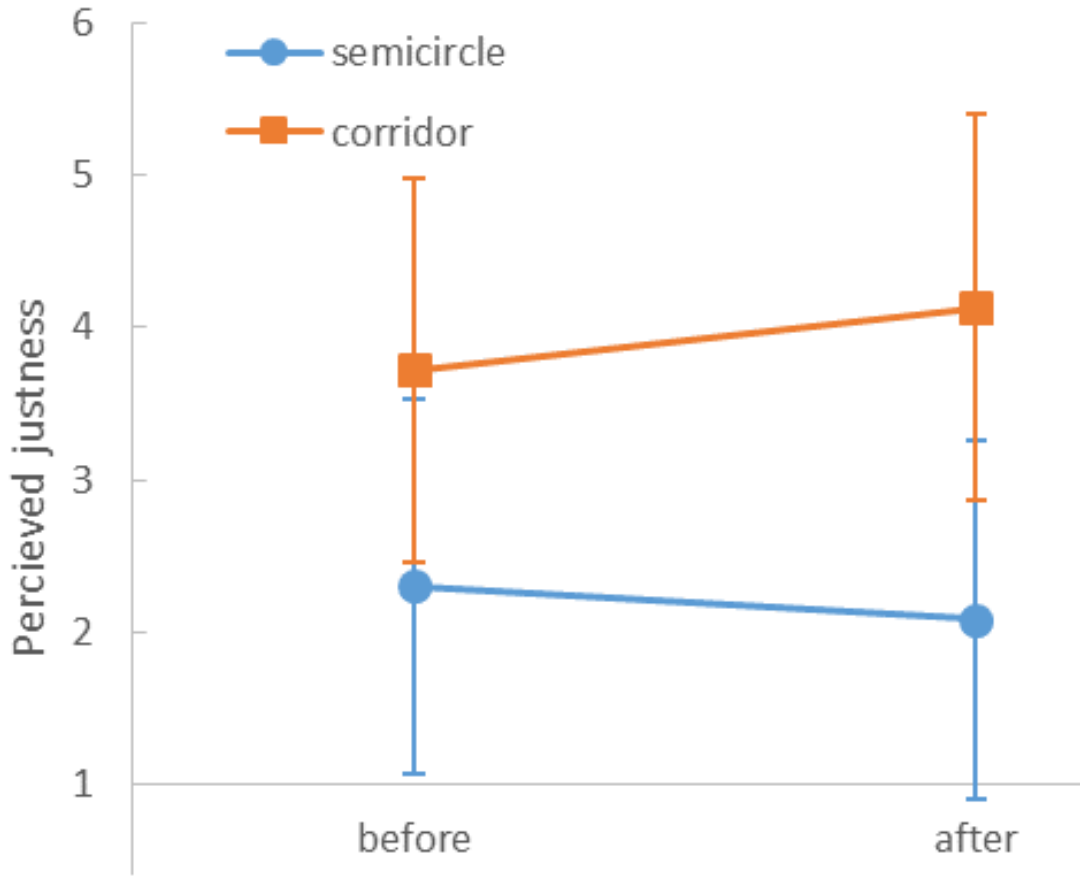
The questionnaire (originally in German) contains four main items: fairness, progress, comfort, contribution to access faster

- 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

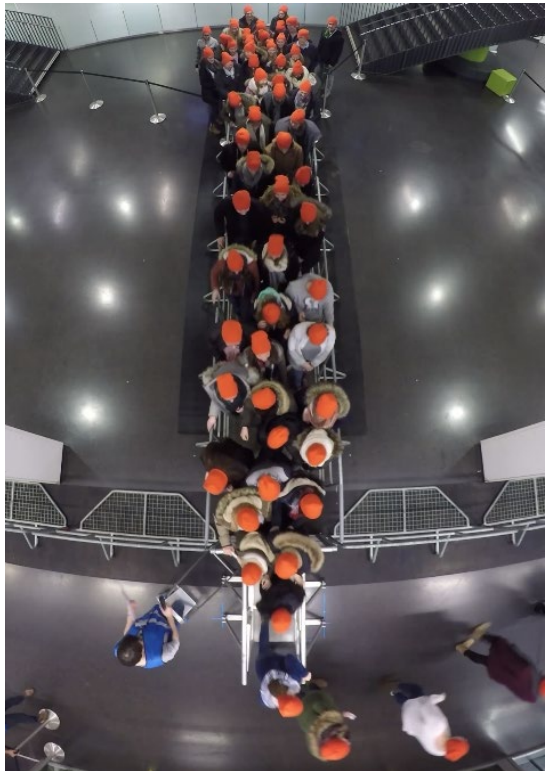
Question

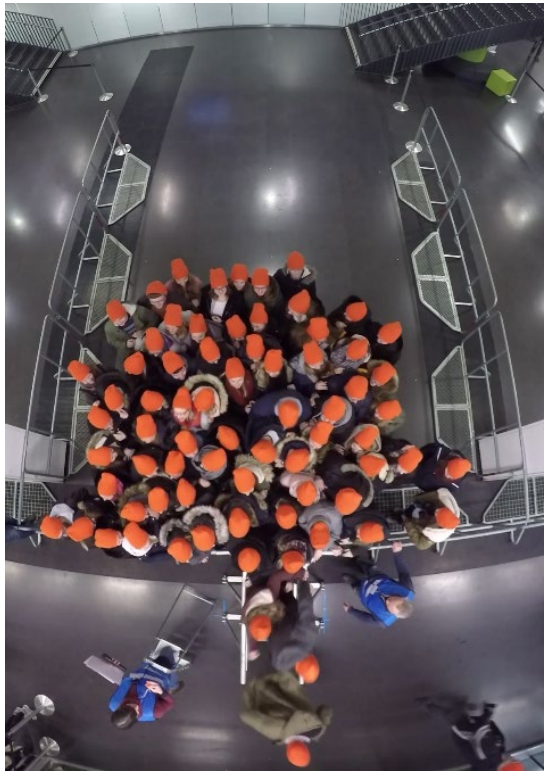
- When do participants queue and when do they start pushing?

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)





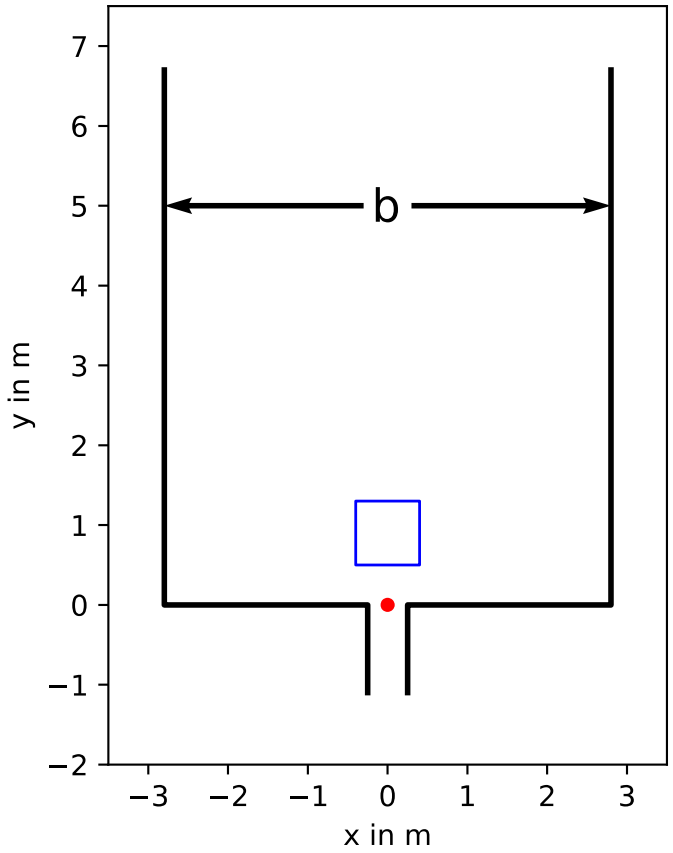
Juliane Adrian, A. Seyfried, Anna Sieben, Crowds in front of bottlenecks at entrances from the perspective of physics and social psychology, Interface 17(165), 20190871, 2020

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



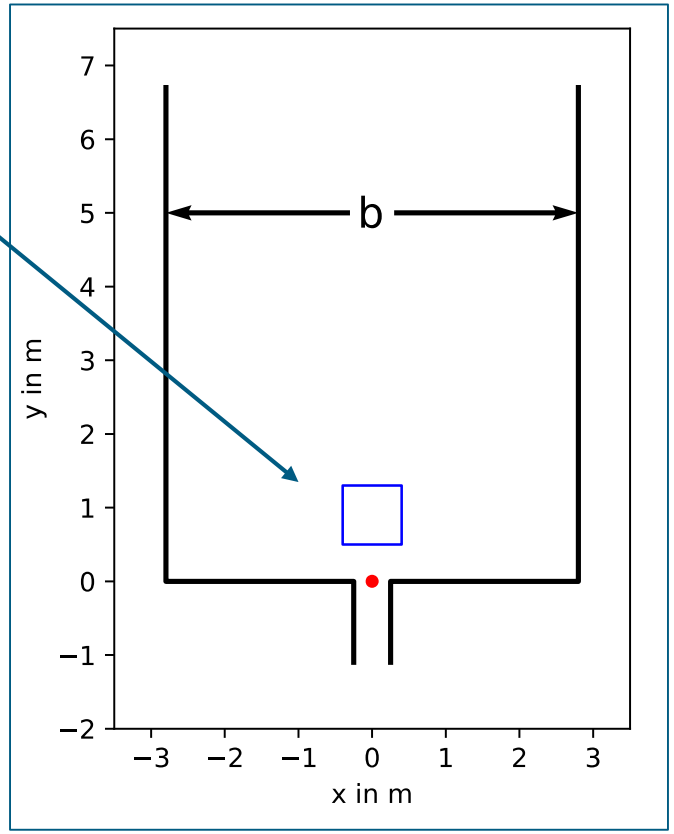
Motivation

- 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

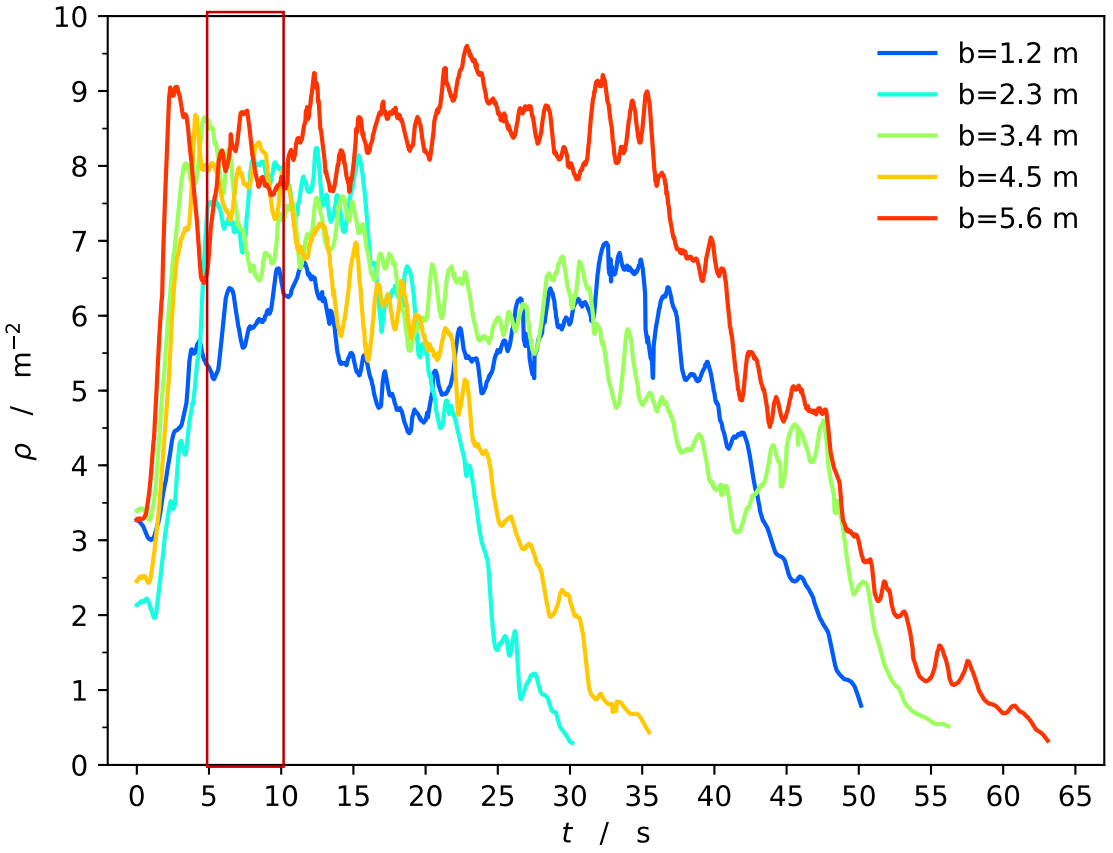
PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

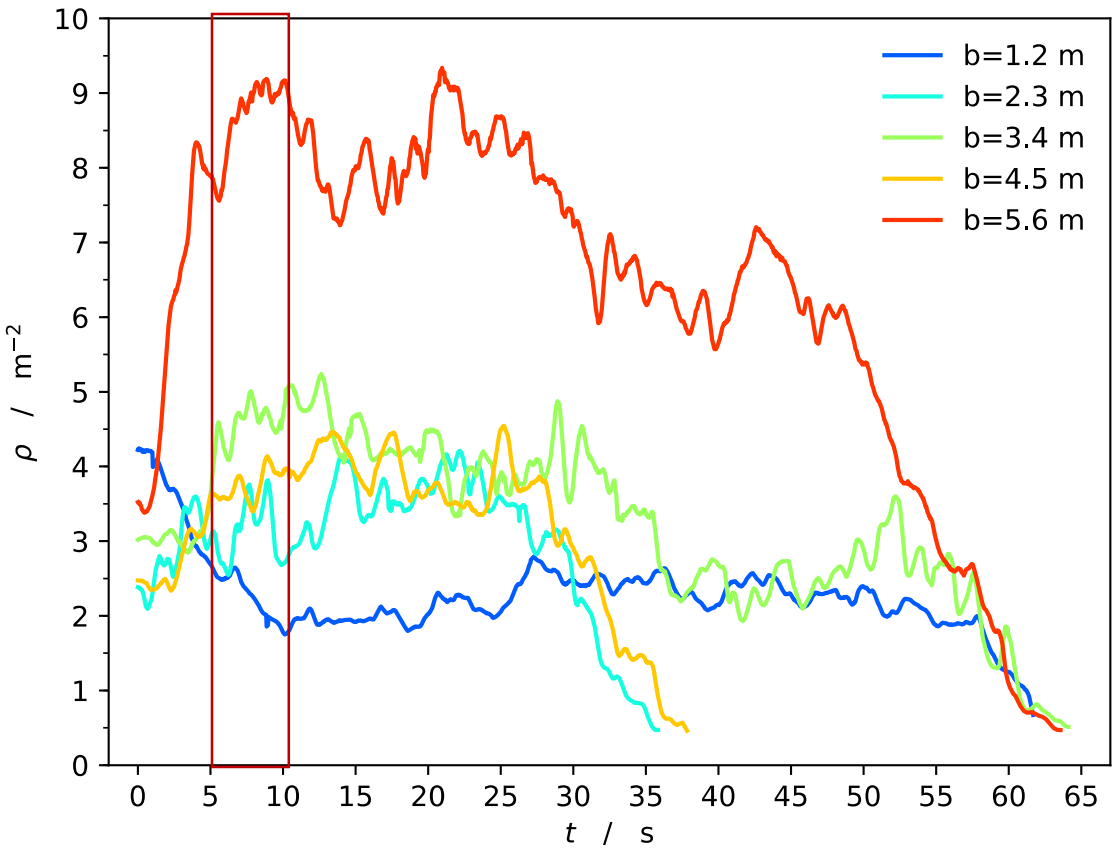
Density within the measurement area



PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

Density within the measurement area

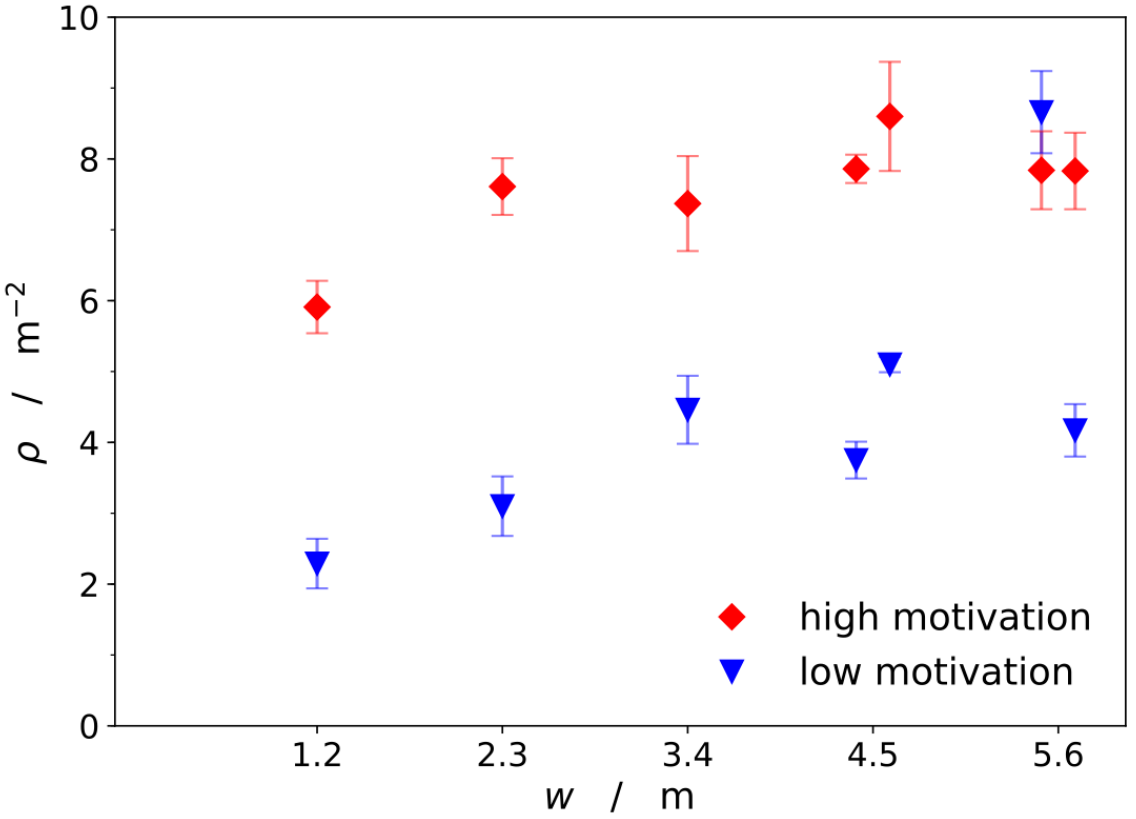




INTRODUCTION

Results

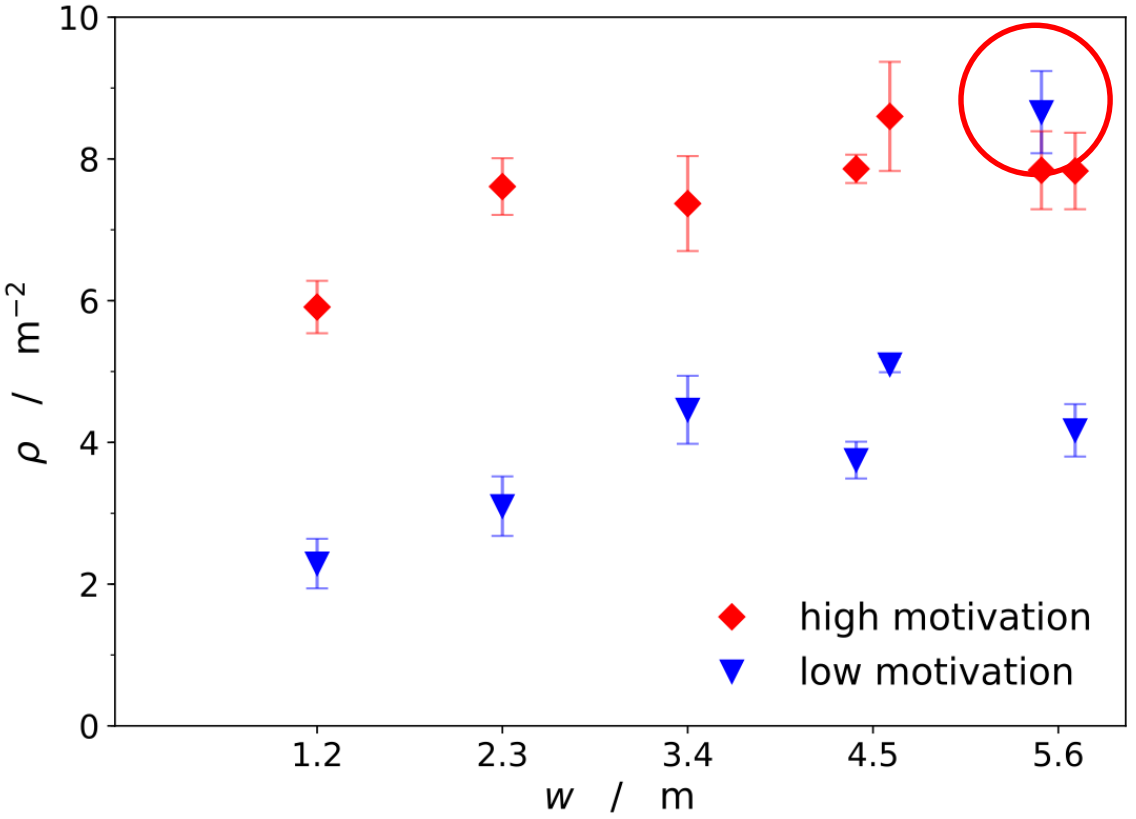
- Density increases with increasing corridor width
- 2 density-levels: dependent on degree of motivation



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:

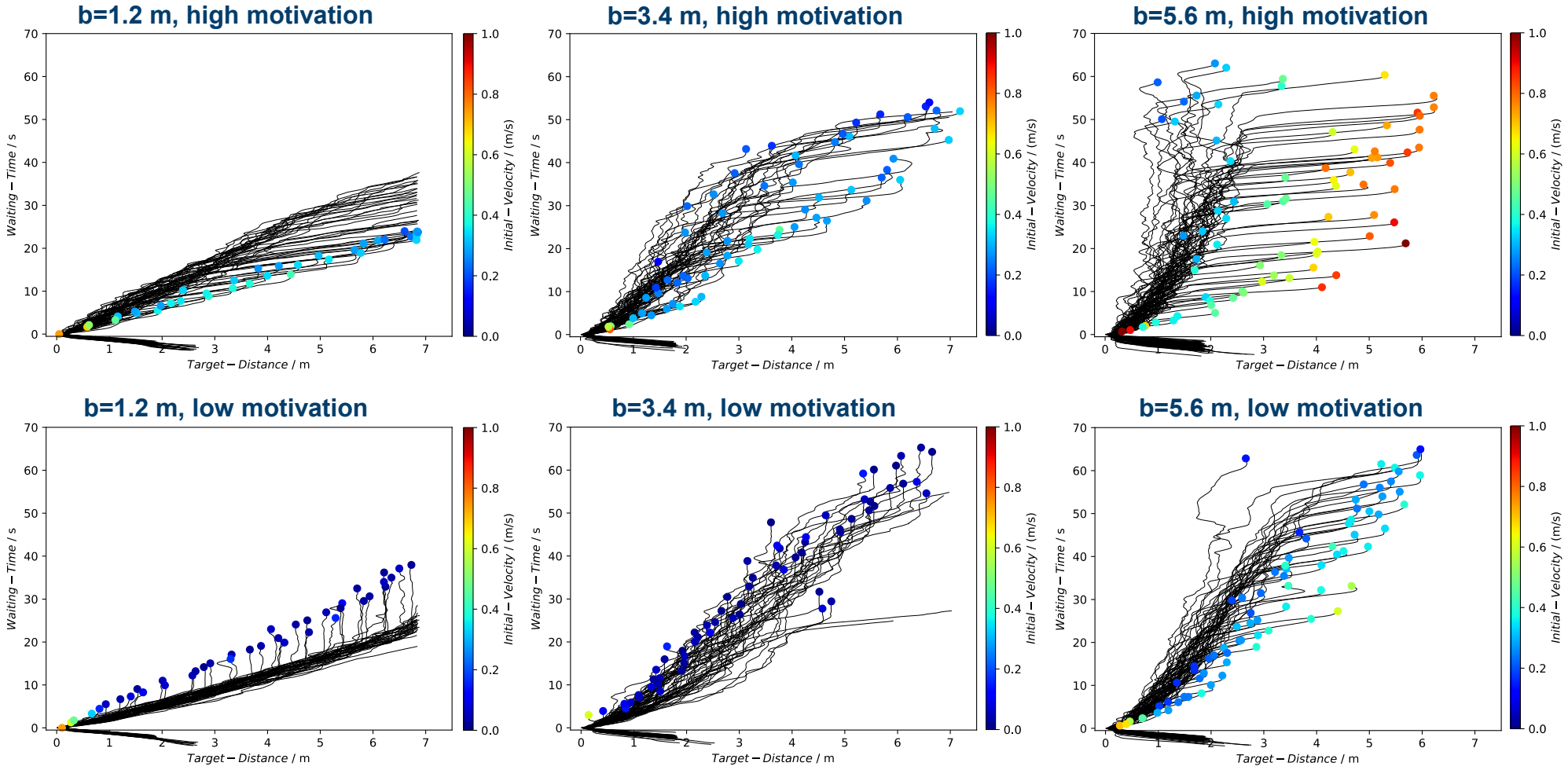


PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II

High motivation

Low motivation

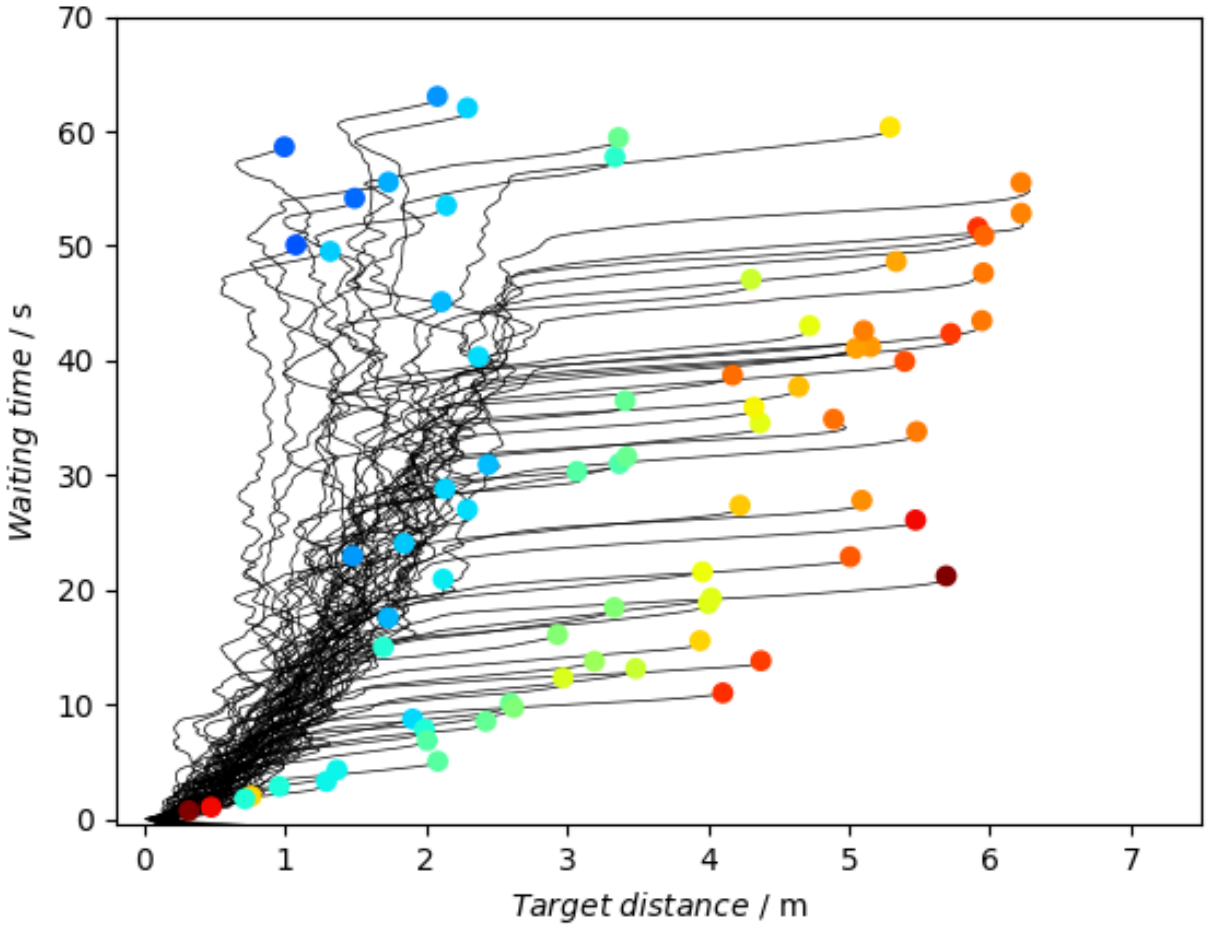
PHYSICS AND SOCIAL-PSYCHOLOGY – EXPERIMENT II



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

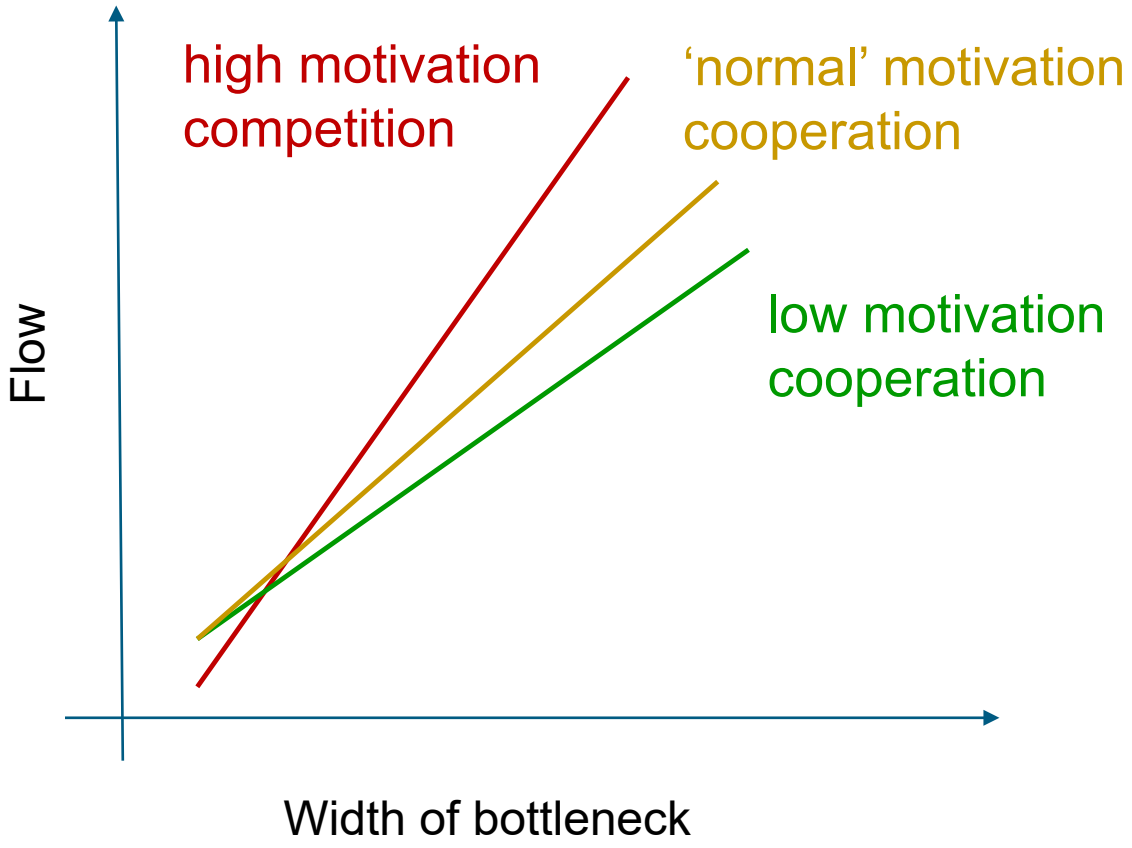
- Physical properties like the width of the corridor has an influence on the dynamics
- But also social-psychological factors, here motivation, could have a strong influence.

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.**

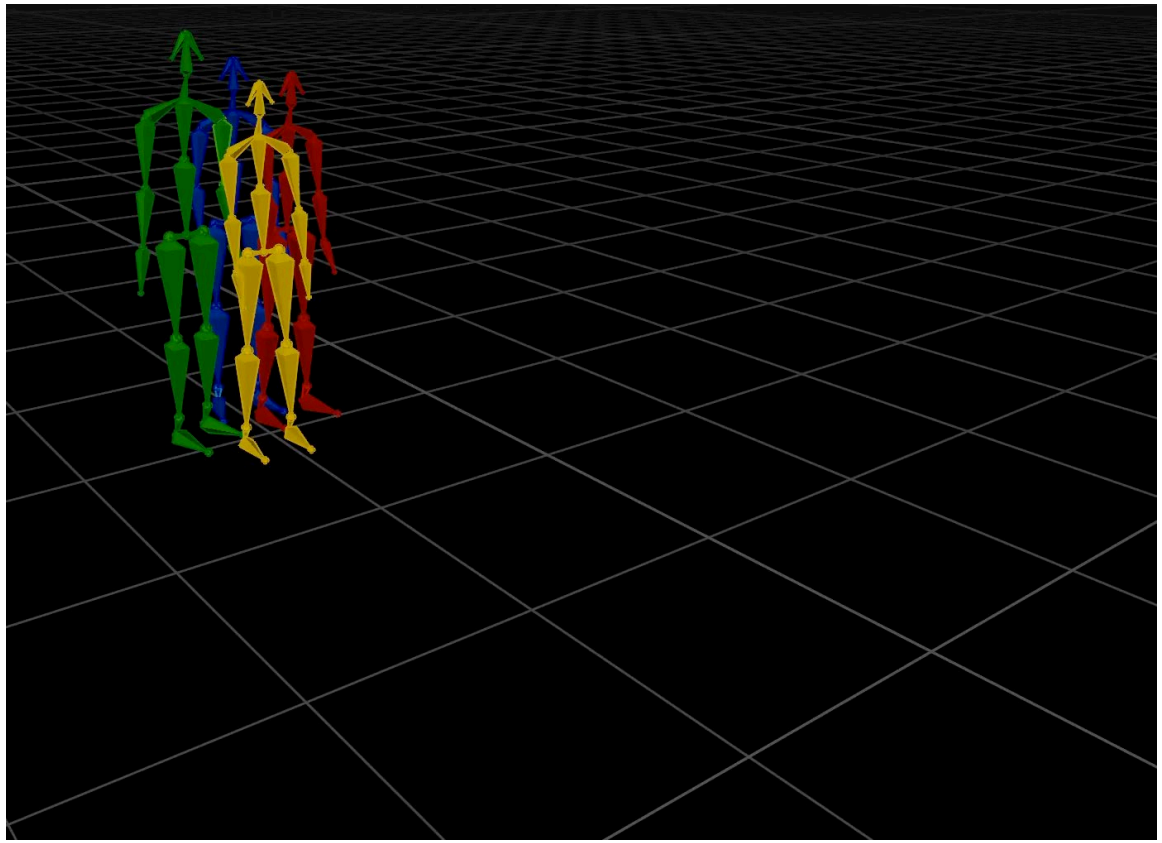


OUTLOOK

OUTLOOK

OUTLOOK

OUTLOOK



Source: Marc Strunz-Michels