Understanding pedestrian-geometry interactions via real-world measurements in variable environments

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Abstract We present a real-world experimental campaign to investigate the impact of spatial geometry on real-life pedestrian dynamics. It hinges on weekly changes of the location of obstacles in a trafficked venue. We show that the geometry effects on trajectories can be quantitatively captured by a continuous variational principle. Notably, our setup bridges the gap between controlled laboratory experiments and large-scale real-world data collection, offering both experimental control and high statistical resolution.

Keywords Pedestrian dynamics, geometry dependency, real-life experiment, variational modeling

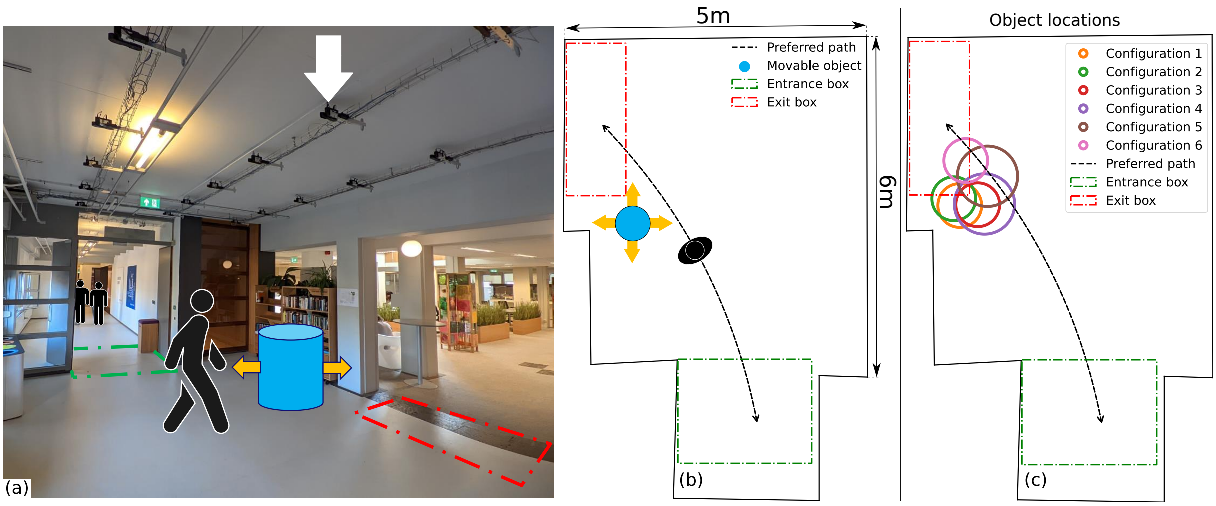

Figure 1: **(a)** Measurement venue at the entrance of the University of Twente library (**(b)**, overhead sketch). On a weekly basis, we perturb the geometry in the proximity of the preferred path (dashed black line) by changing the position of an obstacle (blue cylinder). We anonymously track each pedestrian crossing the area via a grid of overhead sensors (one highlighted by the white arrow), collecting up to 5.000 trajectories per day. **(c)** Obstacle size and position for six configurations between November 2024 and January 2025 (cf. Fig. 2a).

Navigating built environments is key to pedestrian dynamics. Understanding the impact of geometric changes on pedestrian behavior is an outstanding challenge. In fact, the effect of environmental geometry unavoidably couples with individual stochasticity and mutual interactions. Ideally, one could disentangle such an effect through systematic measurements of pedestrian trajectories across numerous geometrical variations. Laboratory measurements offer fine control over the geometry and thus have been used to investigate prototypical scenarios (e.g. bottlenecks [3, 5] and obstacle navigation at crossings [6]). However, the number of trajectories is constrained by participant availability, hindering the capability of quantifying stochastic effects beyond averages. In contrast recent advancements in automated vision have enabled accurate large-scale collection of pedestrian trajectories in real life [2]. While allowing highly-resolved statistics, these campaigns are limited by static or uncontrollable environments.

In this study we combine the strengths of laboratory-based and real-life measurements to understand how generic geometric configurations influence pedestrian movement We achieve this by introducing weekly geometric perturbations in a trafficked real-world environment while anonymously tracking the

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crossing pedestrians (setup in Fig. 1); thousands of users per day, cf. Fig. 2(a)). We observe that each obstacle configuration produces a different position probability and velocity field, one of which is depicted in Fig 2(b).

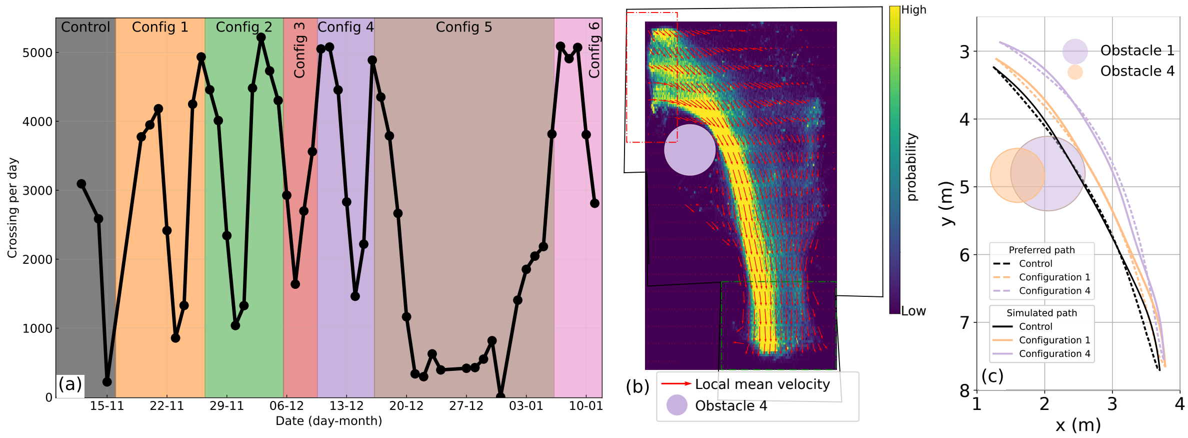

Figure 2: **(a)** Number of trajectories per day, background shades distinguish the configurations (same color coding of Fig. 1(c)). **(b)** Obstacles in different locations reflect in different position probability and velocity fields: case of configuration 4, restricted to trajectories moving from the red to the green area. **(c)** Average pedestrian trajectory in three configurations including control (i.e. no obstacle), comparison between empirical data and prediction by the variational model in Eq. 1.

To understand the mechanisms that regulate the pedestrian-geometry interaction, we assume a rational pedestrian model [4], according to which individual decision-making is driven by the minimization of a hidden cost function (e.g. an interplay between comfort and efficiency). To this end, we explore various continuous variational principles that generalize the proposal by Arechavaleta et al. [1] by including an obstacle penalty term. In Fig. 2c, we report predictions of the average trajectories according to the cost

$$C = \int_0^T \left(\lambda_1 ||\mathbf{v}(t)||^2 + \lambda_2 \kappa(t)^2 + \frac{\lambda_3}{d(t)^2} \right) dt, \qquad (1)$$

which models an interplay of three key terms: a velocity term ($||\mathbf{v}||^2$) that penalizes high unrealistic speeds; secondly, a curvature term (κ^2) that penalizes sharp uncomfortable turns; and lastly a distance-based term (d^{-2}) that penalizes close proximity to obstacles. We estimate the weights $\{\lambda_i\}$ and systematically validate our models by comparing temporal and spatial characteristics of the predicted trajectories with the empirical data.

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