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Pedestrian spatial self-organization according to its nearest neighbor position

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Abstract

The paper describes relation between positions of individuals in a crowd, namely dependence between position of a pedestrian and position of his/her nearest neighbors. Two main characteristics have been analyzed: n^{th} nearest neighbors' spatial and angular distributions. At first sight, people in human crowd seem to be located randomly, however, our findings indicate that there are clearly visible patterns in analyzed characteristics. We discover symptoms of strong correlations between position of closely located pedestrians. Simple, local movement rules for pedestrian are proposed to explain observed patterns.

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Keywords: self organization; spatial distribution; nearest neighbor; crowd dynamics; pedestrian movement rules; emerging behaviors

1. Introduction

In recent years crowd dynamics become a subject of an intensive research. One can find many papers dealing with fundamental relations between experimentally measured quantities, as well as inconsistency in the data obtained from different experiments (Seyfried et al. (2005); Johansson and Helbing (2010)). Another important research area is occurrence of such phenomena as *lane formation*, *flow oscillations*, *faster-is-slower* effect or *zipper effect* (Schadschneider et al. (2008)). Other topics are of interest to researchers' community as well: pedestrian trajectories in different geometries, factors which could indicate occurrence of dangerous situations Helbing et al. (2007), decision-making process and leadership in human crowd and many others. There is also ongoing research dedicated to discover behavioral rules that are responsible for human self-organization phenomena with focus on the basic rules of movement (Moussaïd et al. (2009, 2011); Rio et al. (2014); Wąs et al. (2011)).

Motivated by similar approach used to better understand behavior of animal herds (Ballerini et al. (2008)), we believe that besides of all the areas mentioned above, it is also worth to analyze the relations between positions of individuals in crowd in terms of nearest neighbors.

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In this article, we examine in what relation position of a pedestrian is with position of his/her nearest neighbors. We take into account analysis of two characteristics:

- spatial distribution of n^{th} nearest neighbors,
- angular distribution of n^{th} nearest neighbors with regard to the direction of motion.

We have noticed that these characteristics reveal existence of clearly visible patterns. Pedestrian dynamics simulations suggest that complex crowd behavior may emerge from simple, local movement rules. We believe our findings can help us better explain phenomena like lane formation or zipper-effect

2. Analyzed experiments

For further analysis we used pedestrian movement data from experiments performed in May 2009 in Düsseldorf as a part of the *Hermes* project[1]. Aproximately 350 persons participated in experiments, most of them were students, with 43% female and 57% male, average age was 25 years (± 5.7). The aim of participants was to pass trough a straight corridor with a changing width. Pedestrian trajectories were obtained automatically using *PeTrack* software. Detailed description of experimental setup can be found in Zhang et al. (2011, 2012).

In order to reduce influence of borders we analyze data from the experiments where corridor had constant width. Two such experiments were performed:

- Experiment 1 - corridor 240 cm wide, 246 participants (coded as uo-240-240-240).
- Experiment 2 - corridor 300 cm wide, 349 participants (coded as uo-300-300-300).

3. Nearest neighbors distribution

For given positions of all pedestrians at time t we can find its nearest neighbors. For each person we can sort all other people by increasing distance between them and selected person from neighborhood. The first person with the shortest distance we will call 1$^{\text{st}}$ nearest neighbor, person with n^{th} shortest distance n^{th} nearest neighbor. For a big enough crowd we could analyze arbitrary large n, however, due to the finite size of the experiments from which data comes any analysis beyond 10$^{\text{th}}$ nearest neighbor is unfeasible, because border effects become too significant. Given set of all n^{th} nearest neighbors, we can ask a question how does the mean distance to the n^{th} nearest neighbor change with the n. This relation for data from both experiments can be seen in Fig. 1a. Both the mean distance and its variance increase with increasing n.

3.1. *Angle to the n^{th} neighbor*

Given a reference pedestrian we can not only calculate distance to its n^{th} neighbor, but also an angle at which he can be found with regard to the direction of motion. If the neighbor is directly in front of pedestrian it is at 0°, the neighbor on right is at 90° etc. Given set for angles of all n^{th} nearest neighbors we can construct an angular probability distribution function for a given n. Due to noise in position estimation we decided to use a moving average filter with a window size of 5 to smooth the distribution. Obtained results from both experiments for 8 first nearest neighbors are presented in Fig. 2.

3.2. *Spatial distribution for nearest neighbors*

To gain more insight into the structure of obtained results we decided to calculate spatial distribution of relative positions for n^{th} nearest neighbors in form of a probability histograms for first (see Fig. 3) and second (see Fig. 4) experiment. To show the behavior for higher n we depict 9$^{\text{th}}$ and 10$^{\text{th}}$ nearest neighbors relative position distributions both for first (see Fig. 5) and second (see Fig. 6) experiment together.

[1] http://www.asim.uni-wuppertal.de/en/database/own-experiments/corridor/2d-unidirectional.html

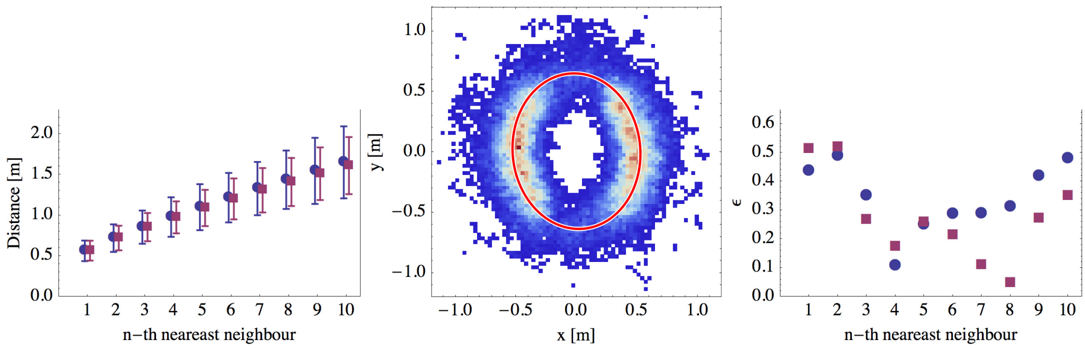

Fig. 1. (a) Dependence of mean distance to the n^{th} nearest neighbor and its variance on n. The results are shown both for first (blue) and second (red) experiment. (b) All 1[st] nearest neighbors positions presented as a 2D histogram, warmer color represent more probable positions. An ellipse fitted to best describe the shape of the data is shown as well (red). (c) Relation between eccentricity of the shape of relative positions distribution for n^{th} nearest neighbor (see (b)) and n for first (blue circles) and second (red rectangles) experiment.

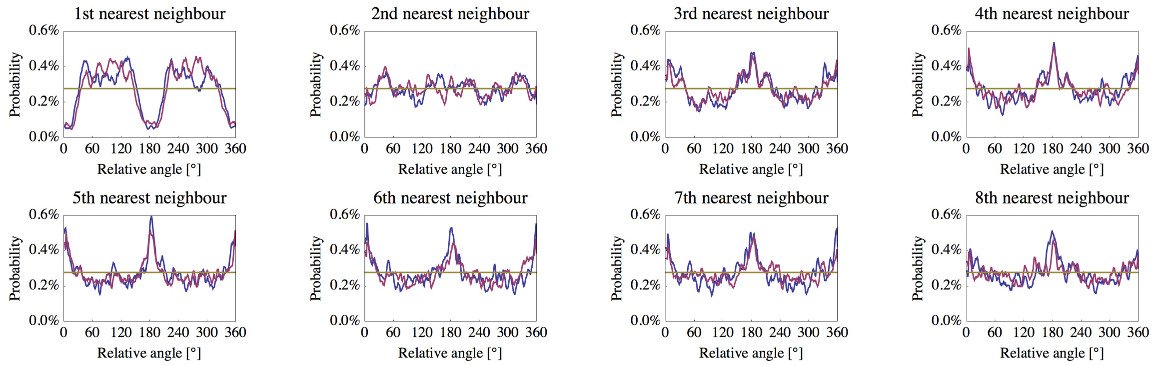

Fig. 2. Angular probability density function for the n^{th} nearest neighbor. To increase clarity the distribution was filtered with a moving average filter with a window size 5. On each plot data from first (blue) and second (red) experiment is shown. An uniform distribution (yellow) is plotted for reference.

3.3. Eccentricity of spatial distribution for nearest neighbors

As can be seen in Fig. 3 and 4 shape of spatial distribution for nearest neighbors is not always circular as intuitively one could expect. In order to methodically investigate this fact we adopted the following procedure:

- For a given n take a set of all relative positions to n^{th} nearest neighbor.
- Find an ellipse best fitting the given set (see Fig. 1b for an example).
- Given lengths of semi-axes i.e. a, b eccentricity ϵ can be calculated:

$$\epsilon = \sqrt{\frac{a^2 - b^2}{a^2}}, \; a \geq b \tag{1}$$

After calculating eccentricity for each set of positions we can plot the relation between it and n as can be seen in Fig. 1c. Values of ϵ close to zero correspond do very circle-like shapes, the closer to 1 the value is the more elliptical shape is.

4. Discussion of the results

As can be seen in Fig. 1 mean distance to n^{th} nearest neighbor is increasing with increasing n. The variance of the mean is increasing proportionally as well. This relation is almost identical for both data sets. One could say that this

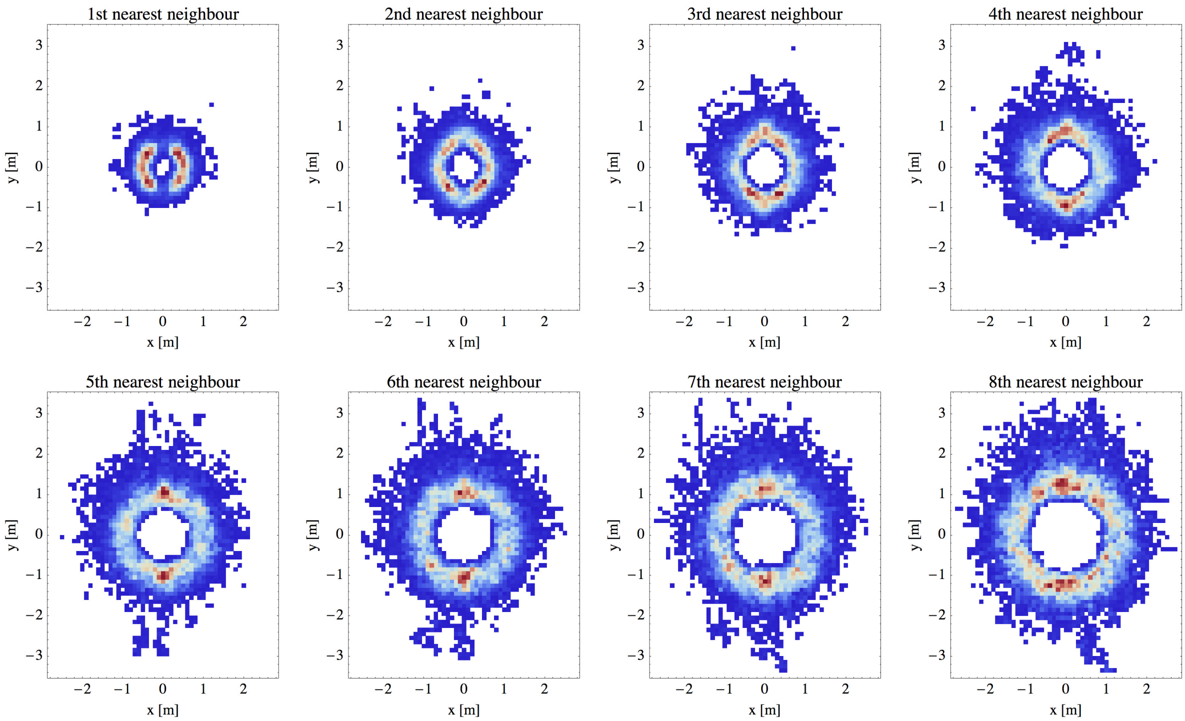

Fig. 3. Spatial distribution of n^{th} nearest neighbor relative positions in form of a probability histogram for first experiment in narrower corridor. Warmer colors represent more probable positions.

relation should depend on density of the crowd, however, too scarce data was included in this preliminary research to draw any definite conclusions.

Similarly as for the mean distance relation, the angular probability distributions are almost identical for both data sets over whole analyzed range of values of n. As seen in Fig. 2 for 1$^{\text{st}}$ nearest neighbor positions directly in front and directly behind are never chosen. On the contrary positions at other angles are equally probable. For $n = 2$ the distribution is almost flat. No direction is preferred. For $n \geq 3$ the positions directly in front and directly behind are significantly preferred.

After investigating spatial distributions (see Fig. 3 and 4) of nearest neighbors positions and relation between eccentricity of those distributions and n a few conclusions can be drawn. First of all, for all range of n the shape of spatial distribution is circular in shape and highly condensed. The highly elliptical shape for the first two nearest neighbors quickly becomes more circular for higher n. For high enough n the shape becomes more elliptical again. The effect is more noticeable for the first experiment which was conducted in narrower corridor. After detailed analysis of spatial distributions for 9$^{\text{th}}$ and 10$^{\text{th}}$ nearest neighbors (see Fig. 5 and 6) it is clear that when typical distance to the n^{th} nearest neighbor is similar to the limiting size of the space the distribution is distorted.

Analyzed characteristics suggests existing repeating patters. Pedestrians tend to avoid very strongly people directly in front of them. The more to the side the closer they allow their nearest neighbor. On the other hand they tend to follow very closely people directly in front of them. These behaviors seem to equalize each other for 2$^{\text{nd}}$ nearest neighbor. Observed patterns could be described by a set of simple "rules": *keep at least a given distance to the person ahead of you*, *follow closely person directly in front of you*, *do not mind people on your sides*. Such rules would explain also other self-organization phenomena emerging in crowd as mentioned in the introduction zipper effect and lane formation.

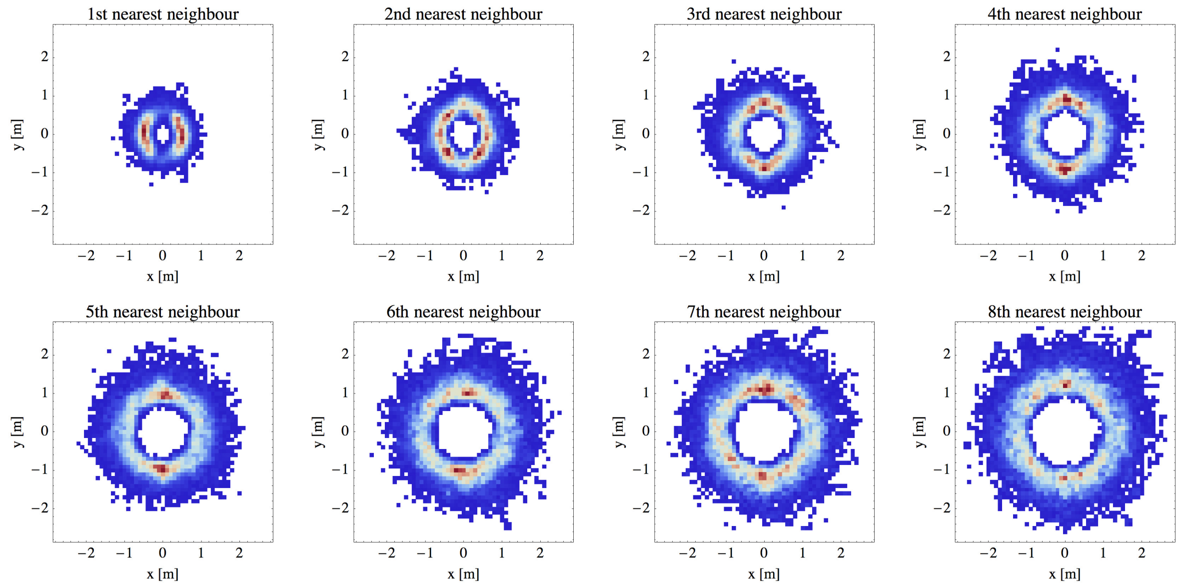

Fig. 4. Spatial distribution of n^{th} nearest neighbor relative positions in form of a probability histogram for second experiment in wider corridor. Warmer colors represent more probable positions.

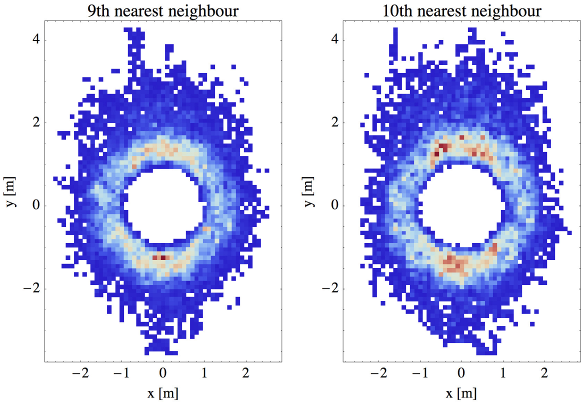

Fig. 5. Spatial distribution of 9^{th} and 10^{th} nearest neighbors relative positions for first experiment (240 cm wide corridor).

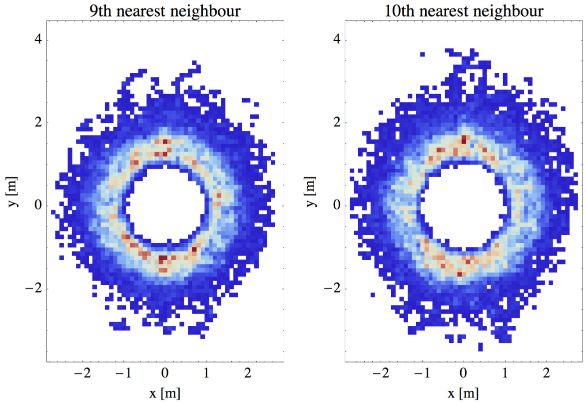

Fig. 6. Spatial distribution of 9^{th} and 10^{th} nearest neighbors relative positions for second experiment (300 cm wide corridor).

5. Summary and future works

The paper showed existence of clearly visible patterns in pedestrian relations to its nearest neighbors in terms of both analyzed characteristics, namely:

- spatial distribution of n^{th} nearest neighbors,
- angular distribution of n^{th} nearest neighbors with regard to the direction of motion.

We observed two distinct behaviors:

- We prefer to never have our 1^{st} nearest neighbor in front of us, the more to the side the closer neighbor can be.

- For $n \geq 3$ the only more preferred positions are directly in front us, other are uniformly probable. Namely we tend to very closely follow people directly ahead of us.

For 2^{nd} nearest neighbor these two behaviors seem to equalize resulting in almost perfectly uniform distribution in terms of both characteristics.

In both experiments the patterns were very similar as well as the behaviors were observed over almost whole range of n. Such very consistent results with no outliers suggest that there should be some very simple local underlying mechanisms. Per analogy to phenomena observed in animal herds observed behavior could be described by following simple "rules": *keep at least a given distance to the person ahead of you*, *follow closely person directly in front of you*, *do not mind people on your sides*.

Discovered relations point also to what mechanisms could lie behind other self-organization phenomena observed in human crowd namely lane formation and zipper effect.

As a continuation of the research we plan to analyze in a similar way data from other pedestrian dynamics experiments and prepare our own dedicated tests to verify stated assumptions. After such verification next step will be building a full mathematical description of observed tendencies that could be used for crowd analysis and computer simulations of pedestrian dynamics.

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