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# The Influence of the Interaction Characteristics on the Movement Dynamics of Pedestrians

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**Abstract** - One of the fundamental properties of pedestrian simulation models is their capability to predict the future movement dynamics of pedestrians depending on the current state of the pedestrian traffic flow, more specifically the walking behaviour of neighbouring pedestrians. This paper investigates the influence of the interaction characteristics on the strength of the reaction of pedestrians walking within a crowd, where the reaction consists of the absolute change in walking direction and speed. This paper studies the influence of the distance headway, time headway, angle of sight, angle of interaction, absolute speed and the number of pedestrians located nearby has been studied. Based on these findings two main conclusions can be drawn, being 1) the operational adaptations of the walking behaviour of pedestrians is influenced by more characteristics of the situation than just the distance headway with respect to the pedestrian walking directly in front of a pedestrian, 2) pedestrians are more likely to change their direction rather than their walking speed when other pedestrians are located within close proximity.

**Keywords:** pedestrian movement dynamics, interaction behaviour, empirical trajectory data sets, time headway, distance headway

## 1 Introduction

One of the fundamental properties of pedestrian simulation models is their capability to predict the future movement dynamics of pedestrian crowds depending on the current state the environment within the infrastructure. Here, the environment consists of the static and dynamic objects as well as the pedestrians located within the infrastructure.

For microscopic models, this entails the prediction of the walking velocity of pedestrians as a result of their interaction with the static and dynamic objects surrounding them. During crowd movements, the interaction with neighbouring pedestrians is generally the most dominant influence. In most contemporary simulation models the reaction, most commonly described by a change in velocity, on these interactions are either computed as 1) an addition of (local) interaction forces (e.g. the Social Force models [1]), 2) the optimal walking velocity given the limitations produced by the interaction with other pedestrians regarding the available space for walking (e.g. Collision Avoidance models [2]), or 3) the optimal solution to the local competition for space (e.g. Cellular Automata [3]).

Even though several of these microscopic simulation models seemingly produce realistic results, the exact influence of neighbouring pedestrians on the operational movement dynamics of a pedestrian is unknown. Previous research into the movement dynamics has been mainly focussed on describing the aggregate features of the traffic flow. Many researchers have studied the relation between the macroscopic flow variables speed, density and flow rate (among others [4, 5, 6]). Generally a negative relation between speed and density is described. However, the shape of this relation differs severely between studies. That is, different values for the capacity, jam density and free flow velocity are found. Several studies indicate that some of the differences between the fundamental diagrams can be explained by the microscopic properties of the interaction between pedestrians.

The first microscopic studies featuring the interaction between pedestrians that qualitatively described the interaction between two pedestrians are [7, 8] and [9]. This last study shows that there is a (cultural) bias in the evasion direction during head-on encounters. [7] indicates, among other things, that the

direction of passing is influenced by the angle of the interaction and that the evasion distance changes depending on the flow situation (i.e. average angle of interaction).

More recently, advancements in measurement techniques more and more allow for a microscopic description of the entire crowd based on individual trajectories, and as such a more quantitative analysis of crowd movement dynamics. These recent studies indicate that the direction of approach [10], the relative positioning of pedestrians [2, 11, 10, 12], their distance headway [13] and their time headway [2, 6, 14] are possible sources of influence which may explain the differences in the aggregate walking dynamics.

However, these papers have not provided definite proof that these variables are indeed essential in the prediction of the operational movement dynamics of pedestrians. Additionally, all researchers have used different data sets featuring very specific flow situations and populations. As a result, the few results on the interaction behaviour are difficult to compare. Moreover, these studies have used very specific definitions for the interaction characteristics that are either discrete in nature (e.g. [11]), specify the movements along one direction (e.g. [13]) or derived from the aggregate properties of the traffic flow (e.g. [14]). Since the spatial component of interaction is disregarded, most of these definitions cannot be used in less stylized flow situations. Consequently, it is questionable whether the relations which are established by previous studies into the influence of the interaction characteristics hold up in more complex interaction situations. Considering these arguments, more research into the influence of spatial characteristics of the interactions is necessary in order to improve our understanding and models featuring the walking dynamics of pedestrians in more complex infrastructures.

The aim of this study is to analyse the influence of the characteristics of the interaction between pedestrians in a crowd on the operational walking dynamics of a pedestrian within that crowd. Here, the interaction is based on the relative location and walking dynamics of neighbouring pedestrians. Moreover, the change in the operational walking dynamics is used to quantify the influence of these characteristics. This study assumes that pedestrians react stronger to interactions that might pose a problem in the near future.

In order to do so, the operational movement dynamics of several hundred pedestrians are systematically analysed. Using empirical trajectory data gathered at four large-scale events in the Netherlands, the reaction of the pedestrians is specified by means of the absolute change in walking speed and direction of a pedestrian under the influence of several characteristics of the interaction such as the current walking speed, the walking direction, and relative positioning of the other pedestrians nearby.

This paper first describes the empirical trajectory data sets and the measures that are used to quantify the operational movement dynamics and the interaction in section 2. The results are displayed in section 3. Section 4 presents the conclusions and some avenues for further research.

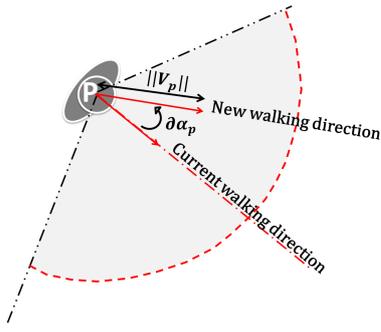
## 2 Research methodology

This section details how the reaction of pedestrians is studied as a result of their interaction with other pedestrians nearby. First, section 2.1 provides a description of the operational movement dynamics of a pedestrian. Section 2.2 mentions the definition of the characteristics that are used to quantify the interaction between two pedestrians. Subsequently, the empirical trajectory data sets used to determine both the reaction and the characteristics of the interaction are introduced in section 2.3.

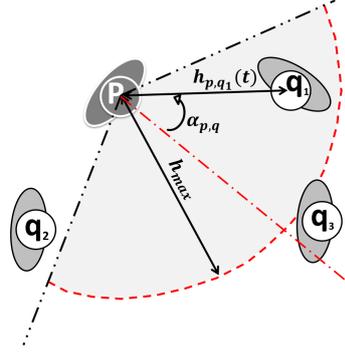
### 2.1 Describing the operational walking dynamics of pedestrians

This study aims to determine the influence of the interaction on the operational movement dynamics of pedestrians. The authors assume that the dominant interactions which might produce a collision in the near future will result in a reaction by the pedestrian under consideration. The reaction of a pedestrian results in a measurable change in the velocity of the pedestrian. This change in the operational walking dynamics of a pedestrian  $p$  can be described by means of two properties, namely:

- *The change in the absolute speed* ( $\delta\|\vec{v}_p(t)\|$ ) - the change in the magnitude of the velocity vector of pedestrian  $p$  between  $t - 0.5\delta t$  and  $t + 0.5\delta t$ .
- *The change in the angular deviation* ( $\delta\alpha_p$ ) - the change in the direction of pedestrian  $p$  between  $t - 0.5\delta t$  and  $t + 0.5\delta t$ .



**Fig.1.** Visualisation of the speed  $\vec{v}_p$  and change in walking direction  $\delta\alpha_p$  of the pedestrian under consideration  $p$ .



**Fig.2.** Visualisation of the distance headway  $h_{p,q}$  and the angle of sight  $\alpha_{p,q}$  for pedestrian  $q$  seen from the perspective of pedestrian under consideration  $p$ .

A visual representation of both variables is provided in figure 1. Both properties are computed based on the original trajectory. Since the trajectory data has already been smoothed during the transcription process no further averaging has been deemed necessary. Pedestrian  $p$ 's instantaneous walking velocity  $\vec{v}_p(t)$  and the change in walking speed are computed by Eqs. 1 and 2. The change in walking direction of pedestrian  $p$  is computed by Eq. 3. In the remainder of this paper the absolute change of the speed and direction are used, since, depending on their character and goal-orientation, pedestrians might speed up or slow down to avoid the same collision.

$$\vec{v}_p(t - 0.5\delta t) = \frac{\vec{x}_p(t) - \vec{x}_p(t - \delta t)}{\delta t} \quad (1)$$

$$\delta\vec{v}_p(t) = \frac{\|\vec{v}_p(t + 0.5\delta t) - \vec{v}_p(t - 0.5\delta t)\|}{\delta t} \quad (2)$$

$$\delta\alpha_p = \frac{\arctan(\vec{v}_p(t + \delta t)) - \arctan(\vec{v}_p(t - \delta t))}{\delta t} \quad (3)$$

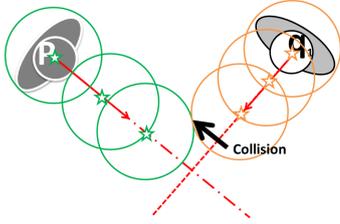
In this formulation  $\vec{x}_p(t + \delta t)$  is the location of pedestrian  $p$  at time  $(t)$  and  $\delta t$  is the time interval between consecutive realisations of the location of pedestrian  $p$  after the filtering procedure described in [15] has been applied. Due to the tracking procedure (tracking heads) and the used definition of walking velocity, the movements of the upper body are taken into account in the velocity computation.

## 2.2 Describing the interaction characteristics pedestrians

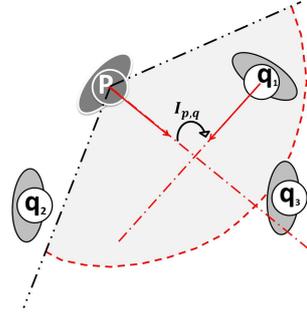
Several studies indicate that the amount of nearby pedestrians (a.k.a. density), their current walking velocity, the distance between the two pedestrians, the angle between the current movement direction of pedestrian  $p$  and the location of  $q$ , as well as the angle between the movement directions of pedestrians  $p$  and  $q$  might influence the operational movement dynamics of pedestrian  $p$ . Here, the distance between two pedestrians can be defined spatially and temporally. Consequently, this study identifies six characteristics of the interaction between a pedestrian under consideration  $p$  and its neighbours  $q$ . The first four interaction characteristics are visualized in figures 2 - 4 and the first three are computed by means of Eqs. 4 - 6. The time headway is computed by means of a heuristic algorithm explained underneath.

- *Angle of sight* ( $\alpha_{p,q}(t)$ ) - the angle between the current walking direction of pedestrian  $p$  and the location of its nearest neighbour  $q$ .
- *Angle of interaction* ( $I_{p,q}(t)$ ) - the angle between the walking directions of pedestrian  $p$  and its nearest neighbour  $q$ .
- *Distance headway* ( $h_{p,q}(t)$ ) - the distance at which the neighbour  $q$  resides relative to the current location of pedestrian  $p$ .
- *Time headway* ( $T_{p,q}(t)$ ) - the shortest time interval a pedestrian  $q$  and the pedestrian under consideration  $p$  require for their radii to touch, given that both continue along their current walking direction with their current speed.

- *Current speed* ( $\vec{v}_p$ ) - the walking speed of pedestrian  $p$  at time  $t$ .
- *Number of pedestrians* ( $N_{r=1m}$ ) - the number of pedestrians which resides within a radius of  $1m$  with respect to the current location  $\vec{x}_p$  of pedestrian  $p$ .



**Fig.3.** Visualisation of the time headway  $T_{p,q}$  for pedestrian  $q$  seen from the perspective of pedestrian under consideration  $p$ .



**Fig.4.** Visualisation of the angle of interaction  $I_{p,q}$  for pedestrian  $q$  seen from the perspective of pedestrian under consideration  $p$ .

$$h_{p,q}(t) = \min | \vec{x}_q(t) - \vec{x}_p(t) | \quad \forall \vec{x}_q(t) \in V_p(t), q \neq p \quad (4)$$

$$\alpha_{p,q}(t) = \arctan(\vec{x}_p(t) - \vec{x}_q(t)) \quad (5)$$

$$I_{p,q}(t) = \frac{\vec{v}_p(t)}{\|\vec{v}_p(t)\|} \cdot \frac{\vec{v}_q(t)}{\|\vec{v}_q(t)\|} \quad (6)$$

Where  $\vec{v}_p(t)$  is the walking velocity,  $\vec{x}_p(t)$  and  $\vec{x}_q(t)$  the locations of pedestrians  $p$  and  $q$  and  $V_p(t)$  the vision field of  $120^\circ$  of pedestrian  $p$  at time  $t$ . In this interpretation, only pedestrians in front of pedestrian  $p$  within  $60^\circ$  of its current angle of movement are taken into account in the computation of the minimum distance headway. The maximum distance headway ( $h_{max}$ ) at which pedestrians are considered to be neighbours is set to be  $3m$ . The last characteristic (time headway) is computed heuristically by determining the time at which the radii (circle with a radius of  $r = 0.2m$ ) of pedestrians  $p$  and  $q$  touch, given that both pedestrians continue along their current path at their current speed.

In a crowd movement situation generally pedestrian  $p$  interacts with several neighbouring pedestrians  $q$  at the same time. This study assumes that the effect of the nearest pedestrian  $q$  on the operational movement dynamics of pedestrian  $p$  is the largest. Here, nearest can be defined both in space and time. Consequently, the influence of all four characteristics are determined for the nearest neighbour in space and time. However, the differences in the results are generally small, therefore in the remainder of this paper, the results are presented regarding the minimum distance headway unless specified otherwise.

### 2.3 Gathering empirical trajectory data

Trajectory data sets have been gathered during five large-scale events in the Netherlands. During each of the events one specific flow situation has been captured on video and transcribed into trajectory data sets. Since there are indications that the interaction behaviour of pedestrians differs between flow situations ([15]), the data of multiple distinct flow situations is combined to get a more complete picture. Instead of identifying the effects of the distinct flow situations, this study is aimed at deriving the generic influence of the interaction characteristics.

The use of several distinct data sets might, however, also introduce additional noise, since the conditions under which the data sets were captured were different (temperature, goal-orientation, population). Moreover, because the data points are not equally spread over the flow situations, and more specifically the total range of the interaction characteristics, a dis-balance might appear in the estimation of the (average) effect of the interaction characteristics. Since a complete set of the interaction behaviours is essential in this paper, these two sources of noise are (for now) considered to be the lesser of the two evils in this study.

These data sets describe the locational information of all pedestrians within the crowd at a detail of more than 10 data points per second. During all events the population consisted mainly of adults

that were walking across the terrain. For a more elaborate description of the cases and the transcription process the reader is referred to [15].

In total 2954 trajectory are used in this study, resulting in 14985 data points detailing distinct reactions on neighbouring pedestrians. Even though the trajectories have been recorded at a frame rate of 10 *fps*, only one data point per two second is used in order to limit the effects of autocorrelation within the data sets. Here, one data point consist of one realisation of all properties of the walking dynamics of the pedestrians under consideration  $p$  and its neighbours  $q$  computed with  $\delta t$  equal to the frame rate of the video data. Pedestrians that walked near the spatial (3m) and temporal boundaries (5s) of the study areas have been disregarded.

Table 1: Case studies used to analyse pedestrian movement dynamics at large-scale events empirically, where UD stands for a uni-directional and BD for bi-directional flow situation.

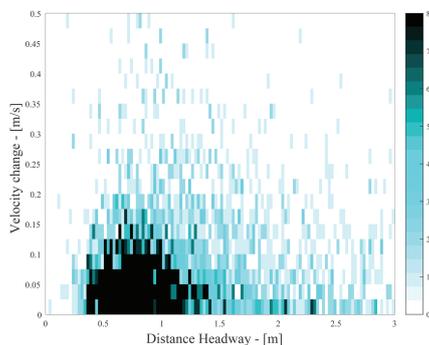
Case study	Abbreviation	Goal	Location	Date	Flow situation
Marathon Rotterdam	M-R	Exit	Rotterdam	14-04-2013	UD-entering
Queensday Amsterdam	Q-A	Music	Amsterdam	30-04-2013	BD - straight
Liberation day festival	LF-W	Music	Wageningen	05-05-2013	Intersecting
4Daagse - day 1: Lent	4D-L	Walking	Lent	16-07-2013	UD-corner
4Daagse - day 2: Wijchen	4D-W	Walking	Wijchen	17-07-2013	UD-straight
4Daagse - day 3: Hatert	4D-H	Walking	Hatert	18-07-2013	UD-corner
Marathon Amsterdam	M-A	Exit	Amsterdam	20-10-2013	Intersecting

### 3 Results

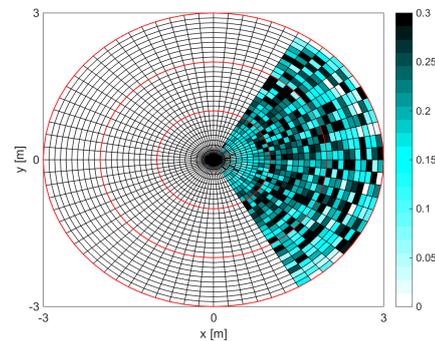
In the following section the influence of these characteristics is determined on both the absolute change in speed and direction. In the following subsections the findings these two reactions on the interaction are discussed separately. First the of the characteristics of the interaction on the change in speed is presented. Accordingly, the influence of the change in angle is studied.

#### 3.1 Change in walking speed

Figures 5 - 12 display the influence of respectively the minimum distance headway, minimum time headway, angle of sight, the angle of interaction, the current speed and the number of pedestrians nearby on the absolute change in the walking speed. Each of the figures display frequency plots, a type of graph in which the colour of a cell represents the number of data points contained within a cell. In this case, a darker cell indicates a higher ‘density’ of data points.



**Fig.5.** Frequency graph of the relation between the distance headway and the absolute change in speed.

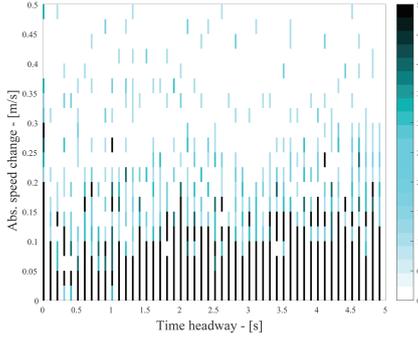


**Fig.6.** Spatial distribution of the maximum absolute change in speed.

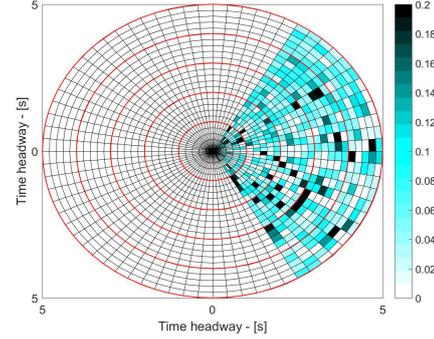
The first of these figures (5) features the relation between the absolute change in speed and the distance headway. A cloud of data points in between the 0.5m and 1.5m is found. Several large outliers are also found within this range. Additionally, the graph shows that a change of the absolute walking speed is

unlikely for distance headways under  $0.5m$ , and that if it occurs it is relatively small. This might be due to the fact that there is no space available for pedestrians to adapt their speed quickly. The majority of the data points is located in the area  $[0.5 \leq h_{min} \leq 1.2, 0 \leq \|\vec{v}_p\| \leq 1.15]$ . For distance headways between  $0.7m$  and  $1.5m$  a decrease in the maximum change of the absolute speed is found. At distances longer than  $1.5m$  the absolute changes in speed seem to stabilize. Although, caution is necessary since the stabilisation of the results can also be due to the general lack of data points for  $h_{min} \geq 1.5$ .

These results indicate that large changes in the absolute speed occur in a limited region surrounding the pedestrian ( $0.5 \leq r \leq 1.2m$ ). A plot of the spatial distribution of the maximum speed change confirms that a region exists nearby the pedestrian ( $r \leq 0.8m$ ) in which a positive trend is found between the distance headway and the absolute change in speed. For  $r \geq 0.8m$  similarly high maximum changes in speed are encountered across the entire vision field. These trends together indicate that the absolute change in speed might be bounded by the distance between the two interacting pedestrians.

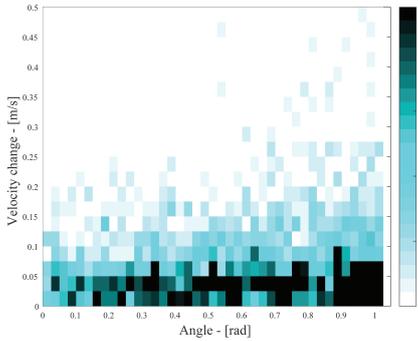


**Fig.7.** Frequency graph of the relation between the time headway and the absolute change in speed.

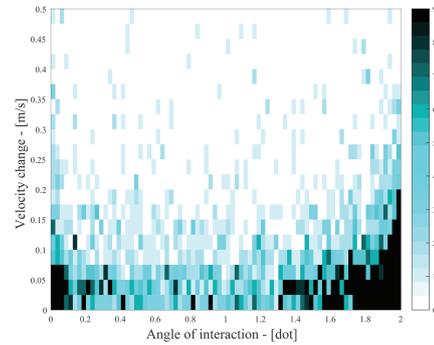


**Fig.8.** Spatial distribution of the average speed change, where a single cell is  $0.1m$  by  $5^\circ$ .

Discrete sets of data points are found due to the heuristic approach used to compute the time headway when studying the relation between the time headway and the absolute change in speed (figure 7). No clear relation can be established in both the frequency plot and an analysis of the spatial distribution of the average absolute change in speed (figure 8). A regression analysis also indicates that no significant relation can be found in figure 7.



**Fig.9.** Frequency graph of the relation between the angle of sight and the absolute change in speed.

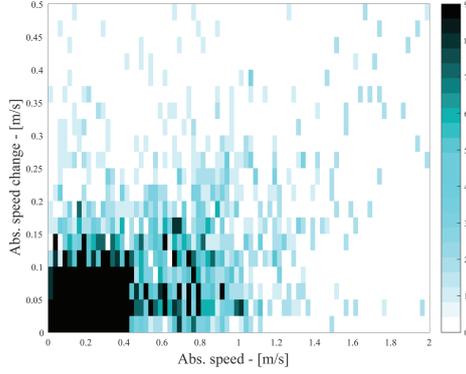


**Fig.10.** Frequency graph of the relation between the angle of interaction and the absolute change in speed.

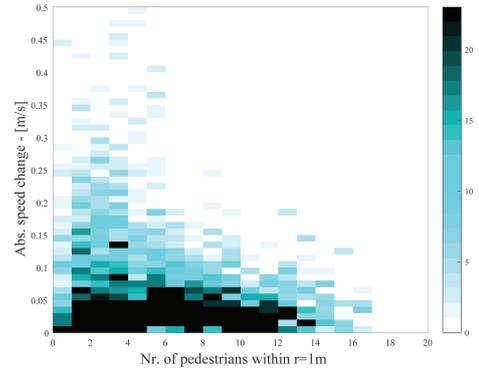
Also in figure 9 no relation between the variables can be discerned. Linear regression confirms that no significant relation is to be found in this cloud of data points. As such, the results illustrates that the angle at which the pedestrian under consideration perceives the nearest other pedestrian has no influence on the change in walking speed of the pedestrian.

In contrast, in figure 10, which depicts the effect of the angle of interaction on the change in speed, two regions are found which contain a higher density of data points (i.e.  $I_{p,q} < 0.2$  (almost bi-directional movement) - and  $I_{p,q} > 1.6$  (almost uni-directional movements)) for which higher absolute changes in speed are found upto  $0.35m/s$ . In between these two regions, generally smaller changes in speed ( $\delta\vec{v}_p \leq 0.15$ )

are found. This results shows that the absolute change in speed is lowest when the velocity vectors of the pedestrians are at an almost  $90^\circ$  angle of each other. It is hypothesized that during interactions under an angle, a change in speed is not effective.



**Fig.11.** Frequency graph of the relation between the absolute speed and the absolute change in speed.

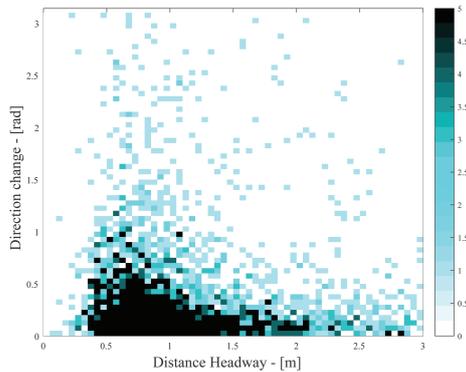


**Fig.12.** Frequency graph of the relation between the number of pedestrians and the absolute change in speed.

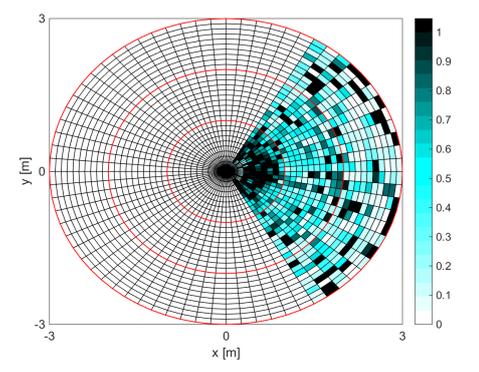
The absolute speed of the pedestrian under consideration was found to have a limited influence on the change in walking speed (figure 11). That is, low walking speeds seem to coincide with small absolute changes in walking speed. Yet, whether this trend is due to behaviour or sample bias is undetermined. Figure 12 indicates that the number of pedestrians located nearby the pedestrian under consideration are negatively influencing the change in walking speed. This last result might indicate that the change of the walking speed is a choice bounded by the opportunity to perform the change in walking speed.

### 3.2 Change in walking angle

Similar analyses have been performed regarding the change in walking direction  $\delta\alpha_p$ . Several comparable trends have been established. That is, the influence of the temporal headway and the angle of sight on the change in walking direction are found to be not significant. However, also some additional trends are established.



**Fig.13.** Frequency graph of the relation between the distance headway and the absolute change in direction.

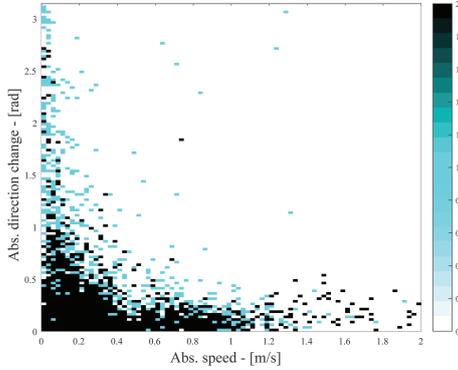


**Fig.14.** Spatial distribution of the average change in direction.

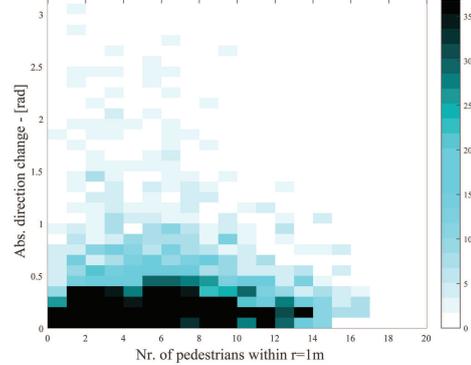
Figures 13 and 14 display the frequency plot of the influence of the distance headway on the change in direction and the spatial distribution of the average change of direction. The first figure illustrates that when the distance headway increases, a large change in direction becomes more and more unlikely. Especially at small distance headways (i.e.  $h_{min} \leq 1$ ) large changes in the absolute speed are found. Figure 14 supports this trend. Here, it is essential to note that the large changes in the average walking direction are found further away from the pedestrian under consideration are generally based on one or two data points. These findings suggest that especially when the distance between the interacting

pedestrians is small, a large change in direction is found.

A last interesting trend in the data is displayed in figures 15 and 16. These frequency plots depicts a inverse relation between the current absolute speed and the number of pedestrians surrounding the pedestrian under consideration in relation to the absolute change of its walking direction. That is, especially when the pedestrian under consideration has a low walking speed and a limited number of pedestrians is surrounding the pedestrian, large absolute changes in direction are found.



**Fig.15.** Frequency graph of the relation between the absolute speed and the absolute change in direction.



**Fig.16.** Frequency graph of the relation between the number of pedestrians and the absolute change in direction.

## 4 Conclusion and discussion

This paper has investigated the influence of the interaction characteristics on the strength of the reaction of pedestrians walking within a crowd. By means of trajectory data sets captured at several large-scale events in the Netherlands, the influence of the distance headway, time headway, angle of sight, angle of interaction, absolute speed and the number of pedestrians located nearby has been studied. With respect to the distance headway negative relations are found with respect to the absolute change of direction and speed. No significant effect could be established regarding the temporal headway. For the angle of sight no significant influence was found. Moreover, especially for very high and very low angles of interaction large changes in the absolute speed and direction are found.

Based on these findings two main conclusions can be drawn. Firstly, it is concluded that the operational adaptations of the walking behaviour of pedestrians is influenced by more characteristics of the situation than just the distance headway with respect to the pedestrian walking directly in front of a pedestrian. Secondly, considering that in the region near to the current location of the pedestrian under consideration an absolute change of direction is found but that the change in the absolute speed is non-existent, it is concluded pedestrians are more likely to change their walking direction rather than their walking speed when other pedestrians are located within close proximity. For larger distances, a speed change is more likely to occur. This change in strategy might be caused by a decrease of the effectivity of the speed-change strategy during interactions at short distances.

In this paper, only the influence of the spatially or temporal nearest neighbour has been taken into account. Many simulation studies, however, indicate that the interactions between a pedestrian and its neighbours might be additive. Moreover, this paper has mainly estimated one-to-one relations between the variables. The interaction effects between the variables, nor the combined effects of multiple variables has been taken into account. This is subject for future research.

## Acknowledgements

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## References

- [1] D. Helbing and P. Molnar, “Social force model for pedestrian dynamics,” *Physical Review - Part E*, vol. 51, pp. 4282–4286, 1995.
- [2] M. Moussaïd, D. Helbing, and G. Theraulaz, “How simple rules determine pedestrian behavior and crowd disasters,” *PNAS*, vol. 108, no. 17, pp. 6884–6888, 2011.
- [3] V. Blue and J. Adler, *Using Cellular Automata. Microsimulation to Model Pedestrian Movement*. Elsevier Science Ltd., 1999.
- [4] J. Fruin, “Designing for pedestrians: A level-of-service concept,” *Highway Research Record*, vol. 355, pp. 1–15, 1971.
- [5] V. Predtechenskii and A. Milinskii, *Planning for Foot Traffic Flow in Buildings*. Amerind Publishing, 1978.
- [6] A. Seyfried, B. Steffen, W. Klingsch, and M. Boltes, “The fundamental diagram of pedestrian movement revisited,” in *Traffic and Granular Flow '05*, A. Schadschneider, T. Pöschel, R. Kühne, M. Schreckenberg, and D. Wolf, Eds., vol. P10002. Berlin: Springer (Berlin), 2005.
- [7] D. Versluis, “Microscopic interaction behavior between individual pedestrians,” Ph.D. dissertation, Delft University of Technology, 2010.
- [8] W. Daamen, S. Hoogendoorn, M. Campanella, and D. Versluis, “Interaction behavior between individual pedestrians,” in *Pedestrian and Evacuation Dynamics 2012 (PED2012)*, U. Weidmann, Ed. Springer International Publishing Switzerland, 2014, pp. 1305–1313.
- [9] M. Moussaïd, D. Helbing, S. Garnier, A. Johansson, M. Combe, and G. Theraulaz, “Experimental study of the behavioural mechanisms underlying self-organization in human crowds.” in *Proceedings of the Royal Society B*, vol. 276, 2009, pp. 2755–2762.
- [10] T. Robin, G. Antonini, M. Bierlaire, and J. Cruz, “Specification, estimation and validation of a pedestrian walking behavior model,” *Transportation Research - Part B*, vol. 43, pp. 36–56, 2009.
- [11] G. Antonini, M. Bierlaire, and M. Weber, “Discrete choice models of pedestrian walking behaviour,” *Transportation Research - Part B*, vol. 40, pp. 667–687, 2006.
- [12] G. Dachner and W. Warren, “Behavior dynamics of heading alignment in pedestrian following,” in *The conference on pedestrian and evacuation dynamics (PED2014)*, ser. Transportation Research Procedia, W. Daamen, D. Duives, and S. Hoogendoorn, Eds., vol. 2. Elsevier, 2014, pp. 69–76.
- [13] U. Chattaraja, A. Seyfried, P. Chakroborty, and M. Biswala, “Modelling single file pedestrian motion across cultures,” in *2nd Conference of Transportation Research Group of India (2nd CTRG)*, ser. Procedia - Social and Behavioral Sciences, P. Chakroborty, H. Reddy, A. Amekudzi, A. Das, A. Seyfried, B. Maitra, D. Teodorovic, K. Srinivasan, L. Devi, S. Pulugurtha, and T. Mathew, Eds., vol. 104. Elsevier, 2013, pp. 698–707.
- [14] F. Johansson, D. Duives, W. Daamen, and S. Hoogendoorn, “The many roles of the relaxation time parameter in force based models of pedestrian dynamics,” in *The Conference on Pedestrian and Evacuation Dynamics 2014 (PED2014)*, ser. Transportation Research Procedia, W. Daamen, D. Duives, and S. Hoogendoorn, Eds., vol. 2. Elsevier, 2014, pp. 300–308.
- [15] D. Duives, “Analysis and modelling of pedestrian movement dynamics at large-scale events,” PhD, Delft University of Technology, October 2016.