Interaction Behavior Between Individual Pedestrians

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Abstract In this contribution, data on pedestrian interactions are analyzed stemming from newly performed laboratory experiments. It has been found that pedestrians perform interaction movements in 88 % of all occasions they meet another pedestrian. These interaction movements consist of lateral and/or longitudinal evasive maneuvers. For crossing situations the approach direction has no influence on the passing side. However, if the approach angle increases and the situation comes closer to bidirectional, pedestrians prefer passing each other on the right hand side. Walking in a hurry increases the probability of passing in front of another pedestrian. Meeting two pedestrians increases the probability of passing at the back. Pedestrians prefer larger lateral evasion in bidirectional situations and larger longitudinal evasion in crossing situations. Moreover, men laterally evade more than women and hurried pedestrians laterally evade more than normally walking pedestrians. Finally, the extent of evasion is larger when small groups are encountered.

Keywords Pedestrian interaction • Laboratory experiments

1 Introduction

Recently, public places such as shopping malls and public transport terminals have become more and more crowded due to increased population size and mobility. Planners and designers of such public spaces have a large need for accurate

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evaluation tools. Microscopic pedestrian simulation models, such as the social forces model [1], Legion [2], and Nomad [3], can provide an objective assessment of a pedestrian facility and quantitatively predict critical areas and bottlenecks in the facility's design.

An important feature of these microscopic models is the ability to represent individual walking behavior in a realistic way to be able to extrapolate towards unknown and future situations. However, detailed observations of this behavior are missing.

Especially these interactions between individual pedestrians appear to be poorly simulated on the microscopic level [4]. Pedestrian movements in these situations mostly look rather abrupt and jerkily where smooth and fluent paths are expected. The main goal of the research described in this paper is to identify the interaction between individual pedestrians.

Based on a literature study, major aspects that influence pedestrian interaction but are not yet included in theory and models, have been indicated. To check the validity of these presumed (existing and new) influential aspects, new laboratory experiments have been performed. The resulting data have been analyzed and implications for microscopic pedestrian modeling are indicated.

The outline of this paper follows the research approach closely. It starts with the setup of the experiments. Then, analyses of the resulting trajectory data are presented. We end with conclusions and recommendations for future research.

2 Experimental Setup

In order to identify and quantify pedestrian interaction movements we collected detailed data on this process in laboratory experiments. Based on the literature study, we have selected the following experimental variables: age, body size, gender, free speed, travel purpose, maneuverability, number of pedestrians and walking arrangements. In the experiments, the influence of the experimental variables on pedestrian interaction movements will be measured. This requires observations on the intended path, where pedestrians are not hindered by other pedestrians. Walking outside the intended path in unhindered walking implies that interaction movements are performed. Interaction movements can be quantified by measuring lateral and longitudinal evasion from the mean trajectory and mean speed graph in unhindered walking. A simple measure to describe pedestrian interaction behavior is the passing side. The participants may pass each other on the left hand side or on the right hand side (in bidirectional and overtaking situations) or at the front or at the back (in crossing situations).

Table 1 shows an overview of the interaction experiments. Each experiment consists of several repetitions performed by different couples (i.e. sets of participants) to guarantee statistical reliability of the results. Each bi-directional and overtaking experiment consists of (at least) 48 runs in total and each crossing experiment consists of 72 runs in total.

Table 1 Overview of interaction experiments

Experiment number	Motion pace		Walking arrangements					Number of pedestrians		Maneuverability	
	N	H	⇅	⇈				1-on-1	2-on-1	O	R
1 (ref.)	X		X					X		X	
2		X	X					X		X	
3		X		X				X		X	
4	X				X			X		X	
5	X					X		X		X	
6		X				X		X		X	
7	X						X	X		X	
8	X					X			X	X	
9	X		X						X	X	
10	X		X					X			X
11	X					X		X			X

N = Normal, H = Hurry, O = nO reduced maneuverability, R = Reduced maneuverability

The experiments have taken place on a single day and only a limited number of participants (1–3) can be active at once. Furthermore, the total workload (i.e. the total distance to be walked) for each participant has to be acceptable, so about 8 km of walking for a full day. The selection of participants has to meet the requirements on the fixed individual experimental variable gender. Taking all this into account, a group of eight participants (four men and four women) was found most suited for the experiments. A walking length of 20 m has been chosen for the final experimental design. Interaction is expected to happen halfway this length, i.e. at 10 m from the initial starting position.

The experiments have been performed in a hall on Friday January 9th in 2009. An impression of the experimental site can be found in Fig. 1a. A concrete floor of approximately 40×16 m is available under a 10 m high ceiling. Video cameras have been attached to the ceiling (see Fig. 1b for an example of the resulting images) and an existing method [5] has been used to derive trajectory data with an accuracy of approximately ± 0.02 m for each recorded image (25 per second) in optimal lighting conditions.

3 Analyses on Unhindered Walking

The aim of this section is to derive boundaries for an intended path in unhindered walking, both in lateral and in longitudinal direction. As presented before, walking outside of these boundaries in interaction situations implies that interaction occurs. The boundaries for unhindered walking depend on the effects of swaying and natural deviation. To derive the swaying amplitude a sine function is estimated through this trajectory using a nonlinear least square method, while upper and lower boundaries

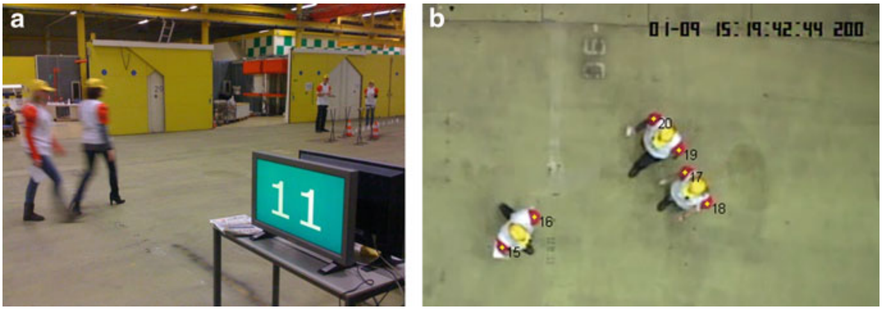

Fig. 1 Overview of the experimental site. (**a**) Site overview. (**b**) Top view from camera

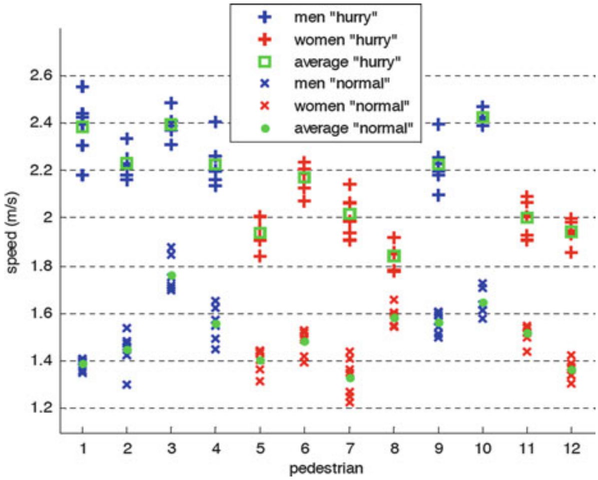

Fig. 2 Walking speed in unhindered conditions

on the amplitude and frequency of the sine function allow for a proper fit. The fitted sine function appears to follow the observed trajectory pretty well, i.e. amplitude, frequency and phase of the sine function resemble the observed trajectory.

Figure 2 shows the observed free speeds calculated over each complete trajectory in unhindered walking. It can be seen that, as expected, almost all hurried runs are performed with a higher free speed than the normal runs. On average, men walk faster than women, especially in hurried conditions. The step length in each run of each participant can be derived from the frequency of the sine function, for it is equal to half the sine period. It follows that the step length (like the swaying amplitude) is individually defined. On average, men have larger step lengths than women, which can be explained by the fact that men on average have longer legs than women have. Moreover, the step length is larger in hurried conditions than in normal conditions. It seems that hurried pedestrians try to maintain their relatively high walking speed with larger step length than in normal walking conditions. In hurried walking conditions the step frequency is on average larger than in the normal walking condition. Apparently, pedestrians increase their motion pace not only by lengthening their steps but also by increasing their step frequency. Moreover, on average men seem to have a lower step frequency than women, especially at normal motion pace. It seems that mainly the larger step length is accountable for the fact that men walk faster than women and that the influence of step frequency is rather small.

Even in unhindered walking deviations occur in both longitudinal and lateral direction, which are visible in the trajectories. Especially the swaying effect should be accounted for in order to correctly assign a deviation from the path to an interaction instead of to a natural sway. Therefore, the trajectories for the individual pedestrians have been corrected for this individual swaying effect and boundaries have been determined by taking two standard deviations from the mean path.

4 Analyses on Interaction Movements

Although literature research has shown that interaction exists between pedestrians, these interaction movements have not been quantified yet. Since trajectory observations are only available around the interaction location, we choose to quantify interaction movements as the extent of lateral and longitudinal evasion. These are defined as the evasion from the individual mean trajectory and the individual mean speed graph in unhindered walking conditions.

The first step is to verify that interaction movements occur in the dataset. For this, the individual repetitions of an individual pedestrian are compared with his individual interaction boundaries. As an example, Figure 3 shows the interaction movements of a participant in the bidirectional interaction experiment. It can be seen that the lower longitudinal interaction boundary is crossed in three runs, i.e. the walking speed has dropped while interacting. Also, participant 3 shows lateral evasion movement to the right hand side (i.e. negative y-value) in all runs. As expected, the results show that 95 % respectively 96 % of the normal and hurried unhindered walking trajectories are within the interaction boundaries. Only 12 % of all trajectories from the interaction runs are within the interaction boundaries, indicating that no interaction movements are performed here. In these cases, the other participant(s) of the couple perform(s) an interaction movement.

Most interaction movements occur in both lateral and longitudinal direction. Mere lateral interaction movements occur more often than mere longitudinal ones, especially for bidirectional situations. An explanation is that in these situations lateral movement by one of the participants is compulsory in order to pass each other, while in crossing situations only a change of walking speed (i.e. in the longitudinal direction) may avert a collision as well. Hurried participants stay within the interaction boundaries more often than normally walking participants (16 % vs. 12 %). If they evade, they tend to do so in the lateral direction: adjusting their

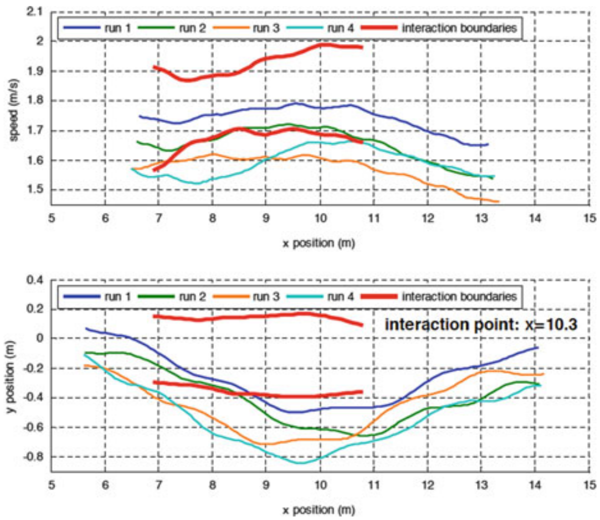

Fig. 3 Bi-directional interaction movements (Participant 3 in couple 13)

walking speed is difficult for hurried participants, since slowing down would annul their hurry and speeding up is laborious for they already walk relatively fast. Also, hurried pedestrians may (enforce and) be granted their intended path more often than normal walking pedestrians.

4.1 Passing Side

Individual pedestrians strongly prefer to pass each other on the right hand side in bidirectional situations (96.6 %). Lateral evasion occurs in line with the passing side. However, a substantial amount (26 %) of the observations shows an increased walking speed during interaction, whereas 22 % shows a decreased walking speed. Most increased walking speed observations are found while a lateral evasion is performed as well. The lateral evasion is likely to be even larger when a small group of two pedestrians has to be passed, explaining why most of the increased walking speeds are found for trajectories from the bidirectional 2-on-1 situation.

For individual overtaking situations the passing side does not seem to be governed by general behavioral or external rules, as is the case in car traffic. The passing side was about equal: in 25 out of 48 runs the person was overtaken on the right hand side. Most participants did have an individual preference: they overtook at the same side during all repetitions. The lateral evasion of the overtaker occurs in line with the passing side (100 % compliance). In nearly half the repetitions the overtaker did not increase his speed to overtake, but walked with a constant speed.

For all crossing experiments combined, in accordance with the expectations, the participants from the right have a slight tendency of passing in front of participants coming from the left (58 %). However, in the 135 ° crossing situation pedestrians from the right hand side tend to pass in front of pedestrians from the left hand side (82 %), which is similar to passing on the right hand side in the bidirectional situation. For crossing situations with an approach angle less than or equal to 90° the passing side is therefore independent of the side of approach.

For all crossing interaction situations 71 % of the observations show an increased walking speed and a lateral evasion towards the destination of the other pedestrian while passing in front or a decreased walking speed and a lateral evasion towards the origin of the other while passing at the back. However, in 67 % of the remaining observations in crossing situations pedestrians may try to solve a collision course by laterally evading to the left hand side. Pedestrian gender has no influence on the passing side in crossing situations (in 52 % of the cases women pass in front of men), but walking in a hurry increases the chance of passing in front (81 %), as does walking in a small group (65 %).

4.2 Extent of Evasion

Table 2 gives an overview of the extent of evasion for the different walking configurations. Pedestrians generally prefer larger lateral evasion in the bidirectional situation and larger longitudinal evasion in crossing situations. This can be explained by the necessity for lateral evasion to continue walking in the bidirectional situation, while in crossing situations longitudinal evasions may avert a collision as well.

It appears that men laterally evade more than women do (26 cm vs. 22 cm). Moreover, men make larger changes in walking speed than women do (0.15 m/s vs. 0.10 m/s). This can be seen as gallantry towards others. However, this gallantry should have appeared in more women passing in front of men in the crossing situations, but this is not the case. The gender issue is therefore recommended for further research.

It seems that pedestrians laterally evade as much while meeting a hurried pedestrian as they do when meeting a normally walking pedestrian (23 cm). It appears that hurried pedestrians take the initiative by performing a lateral evasion movement while interacting. This improves their opportunity to maintain their hurried pace. Pedestrians encountering a hurried pedestrian make larger changes in their walking speed than while encountering a normally walking pedestrian (0.13 m/s vs. 0.10 m/s). In addition, individual interaction movements are larger when more other pedestrians are encountered (43 cm vs. 28 cm).

Table 2 Extent of evasion in several walking arrangements

		Interaction point (m)		Lateral evasion (m)		Longitudinal evasion (m/s)		
	Experiment	μ	σ	μ	σ	μ	σ	Observations
1	Bidirectional	10.0	0.46	0.26	0.18	0.11	0.06	168
3	Overtaking	8.1	1.66	0.35	0.44	0.13	0.09	96
4	Crossing 45°	9.7	0.74	0.09	0.28	0.17	0.16	144
5	Crossing 90°	10.1	0.70	0.23	0.32	0.14	0.14	144
7	Crossing 135°	10.0	0.51	0.16	0.24	0.11	0.09	142

5 Implications for Theory and Models

As has been shown in literature and underpinned better in this paper, existing theories do not correctly describe interaction behavior of pedestrians in situations where two single pedestrians meet each other or a single pedestrian meets a pair. Not only the heterogeneity in pedestrian behavior, but also the difference in behavior in different situations (bi-directional interactions, crossing interactions) is not covered in these theories. However, since these theories do correctly describe pedestrian flow behavior, the problem is in the 'summability' of pedestrian behavior. This means that the behavior of a group of pedestrians is not simply the behavior of the sum of all individuals in the group, which explains the specific research into this group or crowd behavior (see e.g. [5]). Finally, this paper showed that pedestrians in a hurry, or more generally spoken in a different state of mind, demonstrate clearly different behavior from normal walking pedestrians. Current theories do not include these different behaviors. In some facilities (e.g. train stations), this deviating behavior will be more important than in other facilities (e.g. shopping centers). The consequences of this different behavior on the total flow behavior should be investigated in more detail.

6 Conclusions and Recommendations

This paper showed that pedestrians perform interaction movements in 88 % of all occasions when they meet another pedestrian. These interaction movements consist of lateral and/or longitudinal evasive maneuvers.

For crossing situations the approach direction has no influence on the passing side. However, if the approach angle increases and the situation comes closer to bidirectional, pedestrians prefer passing each other on the right hand side. In the bidirectional situation pedestrians strongly prefer passing on the right hand side. Walking in a hurry increases the probability of passing in front of another pedestrian in crossing situations. Meeting a small group of two pedestrians increases the probability of passing at the back. Pedestrians seem to prefer larger lateral evasion in bidirectional situations and larger longitudinal evasion in crossing situations. Men laterally evade more than women and hurried pedestrians laterally evade more than normally walking pedestrians. Finally, the extent of evasion is larger when small groups are encountered.

Several aspects regarding individual pedestrian interaction need further research. Among these are the initiation moment of interaction movements and the effects of gender, body size and age on pedestrian interaction. Also, the effect of 'near collision courses' on interaction movements, the passing side and the extent of evasion is recommended for further research. Including shoulder rotation in pedestrian simulation models may improve the interaction behavior and the visualization of pedestrian movement. This aspects can be investigated with the video data obtained in this study.

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