HUMAN WALKING BEHAVIOR – THE EFFECT OF PEDESTRIAN FLOW AND PERSONAL SPACE INVASIONS ON WALKING SPEED AND DIRECTION

Anna Frohnwieser[1], Richard Hopf[2], Elisabeth Oberzaucher[1]

[1]Department of Anthropology, University of Vienna, [2]CF-Computer GmbH, Vienna, Austria

ABSTRACT

Humans have a natural desire to keep a certain spatial distance to other humans, called personal space (Hall, 1966). If personal space is invaded without consent physiological reactions such as increased heart rate, sweating, and increased blood pressure are triggered (Middlemist et al., 1976).
Using a newly developed system called CCB Analyser the walking patterns of pedestrians in an Austrian shopping center were recorded. Data included number of people, average speed, speed changes, direction changes, and two different measures for personal space, one being personal space in circles around stationary frames and the other being personal space for pedestrians integrating the paths ahead.
Results show that people walk faster when personal space is invaded, and walking speed and direction are changed to a higher degree at high pedestrian flow. These results show how crowded situations require behavioral changes and offer an important insight into the relationship of human walking behavior and personal space.

Key words: *personal space, walking behavior, pedestrians*

INTRODUCTION

Personal space is described by Hall (1966) as a distance of 45-75cm surrounding individuals at which one person can hold or grasp the other with extended arms. Unwanted violations are perceived as intrusive and cause arousal and physiological reactions such as increased heart rate, sweating, and increased blood pressure (Middlemist et al., 1976). Keeping strangers at a distance decreases the possibility of physical aggression and reduces the risk of contagion with diseases (e.g. Troko et al., 2011). A number of studies addressed the shape and size of personal space. However, the findings of these studies vary greatly. For example, Newman and Pollack (1973) found that personal space is bigger in the rear (~120cm) than in the front and on the sides (~60cm each). Hayduk found that personal space is

bigger in the front than in the rear, dropping to zero in the rear if test subjects are not allowed to move their heads (Hayduk and Mainprize, 1980; Hayduk, 1981). These and other studies describe personal space for standing or sitting test subjects, but pedestrians have also been shown to keep a certain distance to other people (Costa, 2010) and to objects.

Pedestrians take the fastest route to their destination (Kretz, 2009), even if that route is crowded (Helbing et al., 2001), and take small detours if that allows them to walk faster (Ganem, 1998). Each person has an ideally preferred walking speed: Among other factors, age, constitution, and sex determine which is the most energy efficient speed for that individual (Ralston, 1958). The average comfortable walking speed usually varies between 1.2m/s and 1.6m/s (e.g. Bohannon, 1997; Costa, 2010). However, if a person needs to get to a destination under time pressure, walking speed increases (Helbing et al., 2001).

To observe the relationship between walking speed and density the fundamental diagram has been established, showing that walking speed decreases with increasing density and more intrusions into personal space. Studies concerning the fundamental diagram usually investigate pedestrian behavior by letting subjects walk on a line behind each other and manipulating the distances between them (e.g. Chattaraj et al., 2009; Kretz et al., 2006; Seyfried et al., 2005). However, in a more natural environment where pedestrians are able to walk next to each other, keep greater distances, and take detours, this kind of behavior is unlikely to occur. Since intrusions into personal space cause physical stress (Middlemist et al., 1976) and studies showed that pedestrians walk faster when stressed (Kamelger and Atzwanger, 2001), we assume that pedestrians increase their walking speed in these situations.

The second focus of this study is walking direction. To avoid an obstacle – be it an object or another person, it is necessary to change walking direction. Gérin-Lajoie and colleagues (2006; 2008) showed that pedestrians are very good at finding the fastest path through a field of obstacles by adjusting their walking direction accordingly, and that subjects keep the greatest distance to obstacles in the front, followed by smaller distances to each side, and a distance of zero in their back. Mathematical theories have been developed to describe and predict navigational paths for obstacle avoidance and route selection (e.g. Fajen and Warren, 2003; Fajen et al., 2003; Fink et al., 2007; Huang et al., 2006). These studies show that obstacle avoidance and steering towards a goal is guided by simple visual cues and does not require complex path planning. The angle and angular acceleration of direction change when avoiding an obstacle depends on the distance of the obstacle from the pedestrian (Fajen and Warren, 2003).

The present study investigated pedestrian behavior with a special focus on personal space. We used a system called CCB (Crowd and Consumer Behavior) Analyser to observe general pedestrian behavior and to calculate possible violations of personal space, thus making it possible to examine the effects of different pedestrian flows and interpersonal distances on pedestrians' behavior.

Our hypotheses were:

1: Higher number of pedestrians and lower interpersonal distances will change walking speed in an inverted U-shaped way: At low numbers

of pedestrians/high distances they will walk at normal speed, at moderate numbers of pedestrians/distances speed will increase, and at high numbers of pedestrians/low distances speed will decrease again due to the lack of space.

2: Higher numbers of pedestrians and lower interpersonal distances will increase the need to change directions while walking.

MATERIALS AND METHODS

The study was conducted using a system called CCB Analyser, which was developed by the Viennese company Yellowfish GmbH. According to a study by Voskamp (2012) who compared data measured with this system to human coded data, the CCB Analyser is most reliable at relatively low pedestrian densities, clear pedestrian flows (e.g. two lanes of pedestrians walking in opposite directions on each side of a corridor), and at locations with little infrastructure such as stairways or escalators. Therefore, we chose a location that largely met these criteria. We placed five sensors on the ceilings of the Gasometer shopping center in Vienna, which take photos of the floor every 0.5 seconds. Computer vision algorithms use the differences between consecutive photos to determine movement parameters such as average walking speed, speed changes, and direction changes. Walking speed was determined by calculating the distance between two tracepoints, i.e. recordings of one person in two consecutive frames, and speed changes were measured by comparing the speed of one person over several frames. Direction changes were recorded by comparing the vectors between consecutive tracepoints.

We defined counter areas, which are rectangular spaces within the observed area. Different parameters are measured for each counter area, the most important being number of people passing through (= pedestrian flow). For this study three square counter areas of one square meter in size were used. They were placed in different areas of the Gasometer shopping center outline.

Since the main purpose of our study was to investigate the personal space of pedestrians, we had to find ways to measure violations of pedestrians' personal spaces. We used two different approaches: The first one was personal space in circles (PSC): Circles of different diameters (1 meter, 5 meters, and 10 meters) were drawn around every person recorded in one frame by the sensors. For each person present within those circles points were allocated depending on the distance from the focus person (a person in the innermost circle would add 3, the middle circle 2, and the outer circle 1 point). The sum of points allocated to the PSC of a person was calculated as a measure of personal space intrusions.

For our second approach we included the general direction of movement of the observed people: personal space in motion (PSM). Based on Gérin-Lajoie and colleagues' studies (2006, 2008), a "house-shaped" personal space was chosen, being biggest in the front and zero in the rear. The distance to each side was 80cm and to the front 160cm. For each person in one picture we calculated the positions of this person in the next frames, extrapolating previous walking speed and walking direction. If another person entered the first person's personal space within one of

the next frames, one point was added for the first person. This was done for every person in each frame, again resulting in a cumulative value. (Fig. 1)
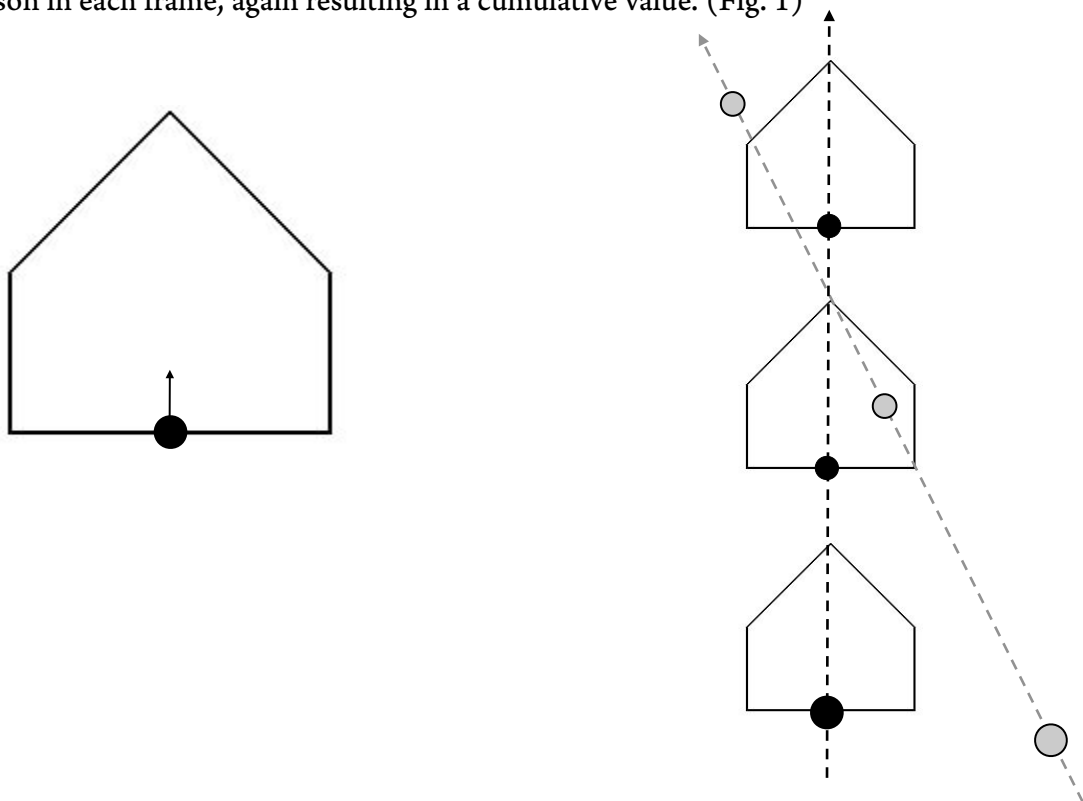

Fig. 1: Personal space in motion. The black dot marks the observed person with an arrow denoting that person's direction. In the left picture the lines show the shape of the personal space, being biggest in the front and zero in the rear. The picture on the right shows a person in a given frame (bigger dot) with two positions/frames of the same person being extrapolated (smaller dots). The grey arrow with grey dots shows a second person's path. At frame 2, the grey path crosses the observed person's personal space. Therefore one point is counted for the observed person.

RESULTS

The data used for this study was recorded from the 22nd of June 2010 to the 13th of November 2010. Altogether, 507 datasets were recorded, with the most important variables being total number of people passing through the counter area (flow), average walking speed, personal space in circles (PSC), personal space in motion (PSM), average change of walking direction in degrees, number of changes in walking direction, average decrease in walking speed in m/s, number of speed decreases, average increase in walking speed in m/s, and number of speed increases. Every set contained a 30 minute time span. For each day, 9 sets were recorded – at three different times of day (08:30am – 09:00am; 01:00pm – 01:30pm; 04:00pm – 04:30pm) and three different counter areas. In total, 253.5 hours (= 10.56 days) of recordings and data of 25 265 pedestrians were analyzed. We cannot exclude to have recorded the same person more than once, since it is not possible to identify individuals with the system that was used.

More violations of circular personal space occurred at higher flow (pedestrians/ counter area/30min) and higher speed. The more violations of circular personal space occurred the more people changed their walking direction (Fig. 2), and the larger the changes of speed were (Fig. 3). The personal space in motion values show a similar pattern, but do not correlate with percentage of people changing direction. (Table 1)

Table 1: Correlations of violations of personal space in circles (PSC) and personal space in motion (PSM) with all other variables. N = number of datasets. Flow = number of observed pedestrians per counter area per 30min. Speed = average walking speed. Angle = average degree of direction change. Angle% = percentage of pedestrians changing direction. SpeedDE = average speed decrease in m/s. SpeedDE% = percentage of pedestrians decreasing speed. SpeedIN = average speed increase in m/s. SpeedIN% = percentage of pedestrians increasing speed.

|			Flow	Speed	Angle	Angle%	SpeedDE	SpeedDE %	SpeedIN	SpeedIN%
Spearman's rho	PSC	Correlation Coefficient	0.749	0.388	0.395	0.230	0.567	-0.067	0.580	-0.022
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	<0.001	0.226	<0.001	0.691
		N	501	332	501	501	332	332	332	332
	PSM	Correlation Coefficient	0.659	0.389	0.195	-0.014	0.401	-0.185	0.403	-0.095
		Sig. (2-tailed)	<0.001	<0.001	<0.001	0.754	<0.001	0.001	<0.001	0.084
		N	501	332	501	501	332	332	332	332
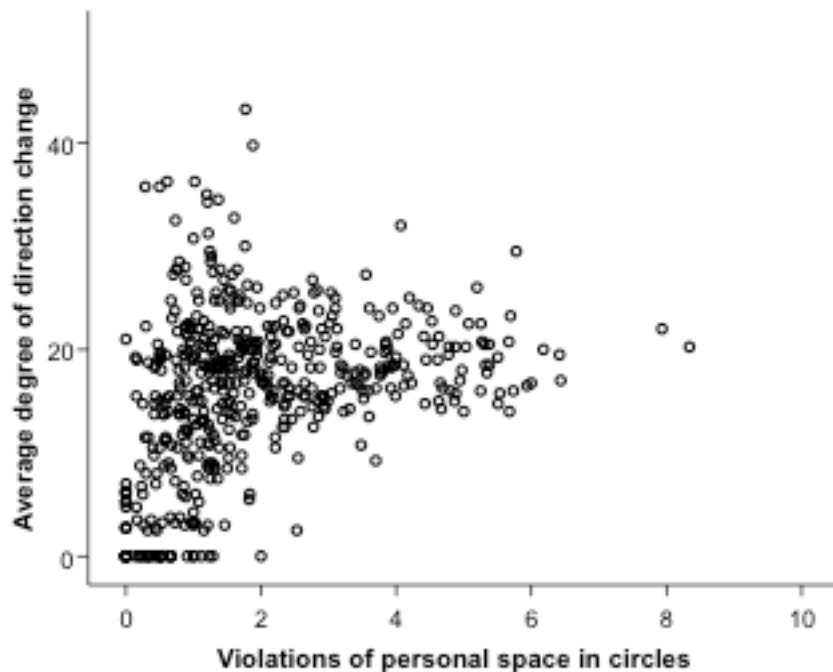
Fig. 2: Correlation of PSC and average degree of direction change. r_s =0.395; p<0.001.
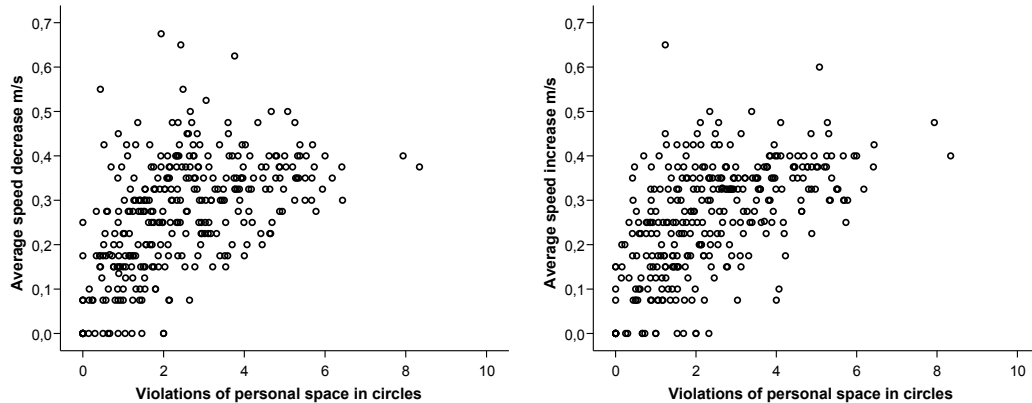
Fig. 3: Correlation of PSC and average speed change. Speed decrease: r_s =0.567; p<0.001. Speed increase: r_s =0.580; p<0.001.

The higher the flow (pedestrians/counter area/30min) was the faster people walked (rs = 0.494; p<0.001) and the more they changed their walking direction (rs = 0.428; p<0.001) and speed (speed decrease: rs = 0.612; p<0.001; speed increase: rs = 0.668; p<0.001).

More people changed their walking direction when more changes of speed occurred (speed decrease: rs = 0.426; p<0.001; speed increase: rs = 0.235; p<0.001). There were fewer direction changes (rs = -0.480; p<0.001) and larger changes of speed (speed decrease: rs = 0.293; p<0.001; speed increase: rs = 0.282; p<0.001) at higher average walking speed. However, a smaller percentage of pedestrians decreased their speed at higher average walking speed (rs = -0.190; p<0.001) and when more pedestrians were present (rs = -0.137; p = 0.013).

 Speed and the personal space values were also correlated partially, controlling for the total number of people observed. Here, average speed correlated negatively with personal space violations (PSC: rs = -0.430; p<0.001; PSM: rs = -0.267; p<0.001).

DISCUSSION

The goal of this study was to determine how human walking behavior is affected by density and violations of personal space, with a special focus on walking speed and direction change.

Supporting our hypothesis, people walked faster at medium flow, changed their direction to greater degrees, and violated each others' personal spaces more often than at low flow. Pedestrians also increased and decreased their walking speed to greater degrees at higher flows, which probably occurs when trying to avoid others by either walking faster to escape them or slowing down to let them pass. To examine this further it would be useful to conduct future studies examining individual trajectories of pedestrians.

In our dataset density was never high enough to limit people's ability to move freely and thus forcing them to decrease their speed. People who changed their direction walked slower, which makes sense considering that step length needs to be reduced when not walking straight, automatically reducing speed (Chung and Hahn, 1999).

Since number of pedestrians and personal space intrusions are linked, we found similar results for both variables. As at high flow, pedestrians also walked faster when there were more personal space intrusions, and the average degree of direction change increased with increasing flow and more violations of personal space. Additionally, the percentage of pedestrians who changed their walking direction increased when personal space in circles was invaded more often.

These results show that a crowded situation requires certain adaptations of walking behavior, likely because of stress (Kamelger and Atzwanger, 2001). Our results also show that the percentage of people who change their walking behavior is the same or even smaller at higher flow, suggesting that not everyone has to adapt their behavior. Physical features such as height and stature or various psychological features might determine who keeps their preferred speed and direction and who changes their behavior in the presence of others.

Our study offers a first insight into the relationship of human walking behavior and personal space, which might be crucial for modeling the flow of pedestrians as well as panic situations.

REFERENCES

Bohannon, R.W. (1997). Comfortable and maximum walking speed of adults aged 20-79 years: reference values and determinants. Age and ageing 26, 15-19. DOI: 10.1093/ageing/26.1.15

Chattaraj, U., Seyfried, A., and Chakroborty, P. (2009). Comparison of Pedestrian Fundamental Diagram Across Cultures. Advances In Complex Systems Vol.12(3) 393-405. DOI: 10.1142/S0219525909002209

Chung, S. and Hahn, J.K. (1999). Animation of human walking in virtual environments. Computer Animation, 1999. Proceedings. DOI: 10.1109/CA.1999.781194

Costa, M. (2010). Interpersonal distances in group walking. Journal of Nonverbal Behavior 34, 15-26. DOI: 10.1007/s10919-009-0077-y

Fajen, B.R. and Warren, W.H. (2003). Behavioral Dynamics of Steering, Obstacle Avoidance, and Route Selection. Journal of Experimental Psychology: Human Perception and Performance Vol.29(2), 343-362. DOI: 10.1109/ROBOT.2009.5152423

Fajen, B.R., Warren. W.H., Temizer, S., and Kaelbling, L.P. (2003). A Dynamical Model of Visually-Guided Steering, Obstacle Avoidance, and Route Selection. International Journal of Computer Vision 54(1/2/3), 13-34. DOI: 10.1023/A:1023701300169

Fink, P. W., Foo, P. S., and Warren, W. H. (2007). Obstacle avoidance during walking in real and virtual environments. ACM Transactions on Applied Percpteption Vo.4(1) DOI: 10.1145/1227134.1227136

Ganem, J. (1998). A behavioral demonstration of Fermat's principle. The Physics Teacher Vol.36, 76-78

Gérin-Lajoie, M., Richards, C.L., Fung, J., and McFadyen, B.J. (2008). Characteristics of personal space during obstacle circumvention in physical and virtual environments. Gait & Posture 27, 239-247. DOI: 10.1016/j.gaitpost.2007.03.015

Gérin-Lajoie, M., Richards, C.L., and McFadyen, B.J. (2006). The circumvention of obstacles during walking in different environmental contexts: A comparison between older and younger adults. Gait & Posture 24, 364-369. DOI: 10.1016/j.gaitpost. 2005.11.001

Hall, E.T. (1966). The hidden dimension. Anchor Books, Doubleday

Hayduk, L.A. (1981). The shape of personal space: An experimental investigation. Canadian Journal of Behavioural Science 13 (1), 87-93. DOI: 10.1037/h0081114

Hayduk, L.A. and Mainprize, S. (1980). Personal Space of the Blind. Social Psychology Quarterly Vol.43(2), 216-223. Stable URL: http://www.jstor.org/stable/3033624

Helbing, D., Molnár, P., Farkas, I.J., and Bolay, K. (2001). Self-organizing pedestrian movement. Environment and Planning B: Planning and Design Vol.28, 361-383. DOI: 10.1068/b2697

Huang, W.H., Fajen, B.R., Fink, J.R., and Warren, W.H. (2006). Visual navigation and obstacle avoidance using a steering potential function. Robotics and Autonomous Systems Vol.54, 288-299. DOI: 10.1016/j.robot.2005.11.004

Kamelger, K. and Atzwanger K. (2001). Die ewige Stadt im Sekundentakt – Der Einfluss von Begrünung auf die Gehgeschwindigkeit in Rom. Homo- unsere Herkunft und Zukunft. Proceedings - 4. Kongress d. Gesellschaft für Anthropologie e.V. (GfA)/ hrsg. M. Schultz, 1. Auflage. Göttingen: Cuvillier, 2000, 176-181.

Kretz, T. (2009). Pedestrian Traffic: on the Quickest Path. Journal of Statistical Mechanics: Theory and Experiment P03012. DOI: 10.1088/1742-5468/2009/03/ P03012

Kretz, T., Grünebohm, A., and Schreckenberg, M. (2006). Experimental study of pedestrian flow through a bottleneck. Journal of Statistical Mechanics: Theory and Experiment P10014. DOI: 10.1088/1742-5468/2006/10/P10014

Middlemist, R.D., Knowles, E.S., and Matter, C.F. (1976). Personal space invasions in the lavatory: Suggestive evidence for arousal. Journal of Personality and Social Psychology Vol.33(5), 541-546. DOI: 10.1037/0022-3514.33.5.541

Newman, R.C. and Pollack, D. (1973). Proxemics in Deviant Adolescents. Journal of Consulting and Clinical Psychology Vol.40(1), 6-8. DOI: 10.1037/h0033961

Ralston, H.J. (1958). Energy-speed relation and optimal speed during level walking. Internationale Zeitschrift für angewandte Physiologie, einschließlich Arbeitsphysiologie, Bd.17, 277-283. DOI: 10.1007/BF00698754

Seyfried, A., Steffen, B., Klingsch, W., and Boltes, M. (2005). The Fundamental Diagram of Pedestrian Movement Revisited. Journal of Statistical Mechanics: Theory and Experiment P10002. DOI: 10.1088/1742-5468/2005/10/P10002

Troko, J., Myles, P., Gibson, J., Hashim, A., Enstone, J., Kingdon, S., Packham, C., Amin, S., Hayward, A., and Van-Tam, J.N. (2011). Is public transport a risk factor for acute respiratory infection? BMC Infectious Diseases Vol.11(16). DOI: 10.1186/1471-2334-11-16

Voskamp, H.A.W. (2012). Measuring the influence of congested bottlenecks on route choice behavior of pedestrians at Utrecht Centraal. Unpublished Master's thesis. Delft University of Technology