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Human Walking Behavior – The Effect of Density on Walking Speed and Direction

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I. INTRODUCTION

Every one of us has made experiences with other people coming too close – in a crowded subway, a restaurant, or on a busy shopping street. We all know what it feels like to be touched or shuffled around by strangers, how uncomfortable it is and how much stress it causes. We feel threatened and disrespected in such situations and try to avoid them as good as we can. This phenomenon is called *crowding* and occurs in different contexts, for example as residential crowding, meaning too many people living in a small space, crowding in work settings and crowding in transportation (see Karlin et al., 1978). To define what crowding is we need to know which distances people usually keep from each other in different situations. In his book "The hidden dimension" (1966) Edward T. Hall defines these distances. What changes for two people keeping different distances from each other is described by sensory factors, such as "How much can I see of the other person?" or "Can I smell, touch or hear the other person?".

1.1. Edward T. Hall – Distances in man

Intimate distance – close phase. This is the distance where physical contact occurs, for example when two people hug. At this distance vision is blurred and details of the other individual can be seen. One can smell, feel and hear the other and sense heat from the other person's body.

Intimate distance – far phase (6-8 inches; 15-20cm). One individual can reach the other with his hands, but the bodies do not touch. Faces are seen as very large and cannot be perceived as a whole, but every detail is perceptible. Voice is held low and the heat and odor of the other's breath can be detected. Crowded subways can bring strangers into intimate distance; however there are tactics to deal with these unpleasant situations, like being as immobile as possible, trying not to touch another person (and if this is not avoidable keeping muscles tense), and not looking at another person.

Personal distance – close phase (1.5-2.5 feet; 45-75cm)**.** At this distance one can hold or grasp the other. Visual distortion of the other's features is no longer apparent. It depends on the relationship of the two individuals towards each other if they stay at this distance or further apart. The better two people know each other and the more they trust each other the closer they usually get.

Personal distance – far phase (2.5-4 feet; 75-120cm)**.** It extends from a point that is just outside easy touching distance to a point where two people can touch fingers if they extend both arms. To perceive the other's face at this distance, the gaze must wander around the face since it cannot be seen as a whole. Hands and body of a seated person can be seen. The voice level is moderate. No body heat is detected, but sometimes the odor of the other individual can be perceived.

Social distance – close phase (4-7feet; 120-210cm)**.** Greater parts of the face can be seen at once, and details of skin texture and hair are still perceivable. The head, shoulders, and upper trunk are visible. Impersonal business occurs at this distance.

Social distance – far phase (7-12 feet; 210-370cm)**.** Business and social discourse at this distance has a more formal character. Desks in offices keep others at far social distance. Fine details of the face can not be perceived anymore, but skin texture, hair and clothes are visible. No heat or odor from the other's body can be detected. This distance allows continuing to work or perform other actions when someone is present without being rude.

Public distance – close phase (12-25 feet; 370-760cm)**.** At this distance an individual can take evasive or defensive action if threatened. No details of the other's face can be seen, but the whole body is visible, including peripheral view of other people present.

Public distance – far phase (>25feet; >760cm)**.** 30 feet (915cm) is the distance automatically set around important public figures, but it can be used by anyone on public occasions. Speech must be loud and slower, and also facial expression is not clearly visible, so that gestures become more important in communication.

For the study presented in this thesis, the most important distance is personal distance, also known as *personal space*.

1.2. Personal space

Personal space is a zone that others are not usually allowed to enter and which surrounds individuals and in some cases small groups (Cheyne and Efran, 1972). Unwanted entrances are interpreted as intrusive and cause arousal (Middlemist and Knowles, 1976) and physical reactions such as increased heart rate, sweating and increased blood pressure. However, who is allowed to enter and who is not, depends largely on the two individuals. Persons with whom we have intimate relationships can come closer than strangers, before discomfort occurs. Personal space is the only human territory that is not bound locally and is also variable in size depending on the individual and the context. Different personal features seem to influence which distances create discomfort and which do not. There are differences in character, for example people who feel confident, powerful and in control keep closer distances than insecure people (Ickinger and Morris, 2001) and people with Type A behavioral patterns (characterized by competitive achievement striving, time urgency, and hostility) who are more responsive to loss of control keep larger distances to others than people with Type B behavioral patterns (Strube and Werner, 1984). Personal space can also be influenced by culture. Hall (1966) gives some anecdotes about Europeans keeping closer distances than North Americans, and he also claims that each cultural group that lives in North America uses space differently (see Baldassare and Feller, 1975 for a review). Baxter (1970) showed in his study that Americans of Mexican origin stood very close, Anglo-Americans kept intermediate distances and African-Americans kept the largest distances from each other. He also found that female-male groups stayed at the closest distances, female-

female groups at intermediate distances and male-male groups kept the biggest interindividual distances.

People erect boundaries to preserve their personal space – for example pile books between each other in a library or turn their bodies away from each other in a crowded subway (Taylor, 1988).

1.2.1. Personal space – an evolutionary view. Why do humans have a natural need to keep distances from each other and feel discomfort when those distances are disrespected?

Biological explanations are simple. Keeping strangers at a distance that allows physical contact only with extended arms if at all decreases the possibility of physical aggression. If you do not know someone or do not trust him it is better to not let him close enough to touch you, because he might be hostile to you.

Another reason for keeping personal space is to reduce the risk of contagion with various diseases. When big numbers of people live in a relatively small space and you do not know most of them anyone could be carrying a contagious disease. Staying away from others limits the risk of catching a virus by not letting strangers touch you or sneeze or cough in your direction. For example, the risk of caching influenza increases dramatically for people who use public transport, where they are forced to stay very close to strangers (Troko et al., 2011).

Personal space also forms around groups of people that belong together in some way, like friends sitting in a café or co-workers standing next to each other in a hallway. Staying close to each other and away from others shows that those people belong together and would probably stick together in any form of confrontation. It is also easier to take care of children when you are in a group than when you are alone, so safety is another reason for personal space around groups.

People forming groups maintain a certain degree of privacy because others are usually reluctant to disturb people who are interacting, for example by walking between them (Cheyne and Efran, 1972).

Personal space can also be described for animals. One example is the observation of captive polar bears by Renner and Kelly (2006), which showed that these normally solitary bears always keep a minimum distance from each other, thus limiting aggressive behaviour. This distance is often referred to as “social distance” or “critical distance”, which is the minimum distance that reduces aggressive behaviour, for example in cats (Juabe-Díaz, 1999) or in turkeys reared for commercial use (Buchwalder and Huber-Eicher, 2004).

1.2.2. The size and shape of personal space. Different studies have been conducted to find out how personal space is shaped and which size it normally has. However, the findings of these studies vary greatly. For example, Newman and Pollack (1973) found that personal space is bigger in the rear (~4 feet) than in the front and on the sides (~2 feet each). They also observed a bigger personal space for deviant adolescents than for normally behaving ones, indicating a personality factor in the size of personal space.

Leslie Hayduk’s studies contradict Newman and Pollack, since he found that personal space is bigger in the front than in the rear (Hayduk and Mainprize, 1980; Hayduk, 1981). He compared the personal space of sighted and blind people and found out that approaching them creates the same discomfort for both groups at the same distances, indicating equal personal spaces. In another study (Hayduk, 1981) he investigated personal spaces of sighted test subjects to find out whether visual mechanisms have an influence on size or shape of personal space. His study showed that the mean distance for frontal approaches, at which people began to feel uncomfortable, was 59cm, which would be within the close phase of personal space (Hall, 1966). He found that personal space is noncircular, with a decline from a maximum frontal distance to a minimum rear distance. When people were not allowed to move their heads the use of peripheral vision increased the size of personal space at these positions, making the largest distance occur half-way between the head and body front. Also, rear distances dropped to almost zero, since people were not allowed to look behind them and could not see the experimenter.

As described above there are many different study results about the size and shape of personal space, so that it seems to be very variable. In their 1984 study, Strube and Werner observed different sizes in personal space for people with different behaviour patterns (Type A – competitive, hostile, in need for control over the environment and Type B – defined by the absence of Type A characteristics) and for people in different situations. Their results show that Type A people in a customer situation preserve the biggest personal space whereas Type B people in a salesperson situation have the smallest personal space. This is just one of the many settings that make the concept of personal space very important.

The need for privacy and distance to others also influences which seats we take in a restaurant (Robson, 2008) and on trains (Evans and Wener, 2007) and how groups of people sit down at a table (Thompson et al., 1979).

Contrary to these studies, which all describe personal space for standing or sitting people, the present thesis deals with the personal space of pedestrians. This is why we first have to take a look at the typical behavior of pedestrians:

1.3. Pedestrian behavior

There is a small set of certain rules that every walking person follows unconsciously. Pedestrians always like to take the fastest route to their destination (Fajen and Warren, 2003), 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 a desired natural walking speed, dependent among other factors on age, constitution and sex, which is the least energy-consuming speed for that person (Ralston, 1958). The mean comfortable walking speed is different for different groups of people (e.g. old and young people, women and men, etc.), and lies usually between 1.2m/s and 1.6m/s (e.g. Bohannon, 1997; Costa, 2010; Henderson and Lyons, 1972; Vallis and McFadyen, 2003). However, if a person needs to get to a destination within a short amount of time walking speed increases (Helbing et al., 2001).

Pedestrians like to keep a certain distance between each other (Costa, 2010; Johansson, 2009) and to objects (Moussaïd et al., 2011) and change their walking speed to maintain those distances (Konečni et al., 1975), They are also very good in finding the fastest path through a field of obstacles (Gérin-Lajoie et al., 2007).

Since other people can be considered as obstacles when we are walking, it is important to know how pedestrians avoid obstacles.

1.4. Obstacle circumvention

Gérin-Lajoie and his colleagues have done studies on obstacle circumvention, investigating which distances people keep from objects and other people. The shape of these distances combined looked a bit like a house – with a maximum distance in the front, smaller distances to each side and a rear distance of zero. In one of their studies (Gérin-Lajoie et al., 2006) they compared older and younger adults walking past stationary or moving obstacles. The test subjects walked slower when the obstacle moved and when they did not know the movement's direction beforehand. Older adults preserved a larger personal space to the objects as younger adults. In a similar study (Gérin-Lajoie et al., 2008) the researches found out that personal space kept between the test subjects and the obstacle did not change with walking speed, and that personal space was bigger on the left side of the test subjects than on the right. A reason for this may be that most test subjects were right-handed and kept a smaller safety margin on their dominant side.

1.5. Hypotheses

This present study aims to combine the investigation of pedestrian behaviour with the investigation of personal space. As shown in studies about the avoidance of obstacles (e.g. Gérin-Lajoie et al., 2006; Gérin-Lajoie et al., 2008), moving people always keep minimum distances to objects and to others. However, it has never been shown which measures pedestrians take to avoid situations in which these minimum distances might be invaded. We used a system named CCB Analyser to observe general pedestrian behaviour and to pre-calculate possible invasions into personal space, thus making it possible to examine the effects of different densities and interpersonal distances on pedestrians.

According to the study design the hypotheses were:

1 Higher density of people and lower interpersonal distances will change walking speed, most probably in a U-shaped way: at low density/high distances they will walk at normal speed, at moderate density/distances speed will increase because of stress (Konečni et al., 1975) and at high density/low distances speed will decrease again due to the lack of space.

2 Higher density of people and lower interpersonal distances will increase the need to change directions while walking.

II. METHODS

2.1. CCB Analyser

The study was conducted using a system called *CCB Analyser*, which was developed by the Viennese company Yellowfish GmbH (Fig.1). The system consisted of five sensors placed on the ceilings of the Gasometer shopping center, which took photos of the floor every 0.5 seconds. These photos were then compared by the software to find out if a person had changed his/her position from one picture to the next. This way, the system can track people through an observed area, making it possible to measure speed, density and other parameters. The software codes all of the measured parameters into colors in different scales, so that differences and changes can be easily detected. Also, there is the option to see all the measured values in numbers in a 50cm x 50cm grid throughout the observed area (Fig. 2). The program gives out all objects that did not move within the observation time as a background picture, usually showing the floor and furniture in the area for easier orientation. It is also possible to define so called *counter areas*, which are rectangular spaces within the observed area. Different parameters are calculated by the program for each counter area; the most important being number of people passing through.

For this study, square counter areas of one square meter in size were used, each including four grid squares (Fig.2). Three counter areas were placed at different areas of the Gasometer outline. The places were chosen for being different in terms of density and of directions pedestrians usually walk there. Counter area 1 was located in a corridor approximately 5 meter wide with a restaurant on one side (Fig.1), which was used frequently by people walking either from the left to the right or from the right to the left. Counter area 2 was located at the end of another corridor, where it gets narrower before it opens into a hall. People there walked in different directions and took different turns to get to their destinations. Counter area 3 was placed at a crossing, where people could come from three different directions.

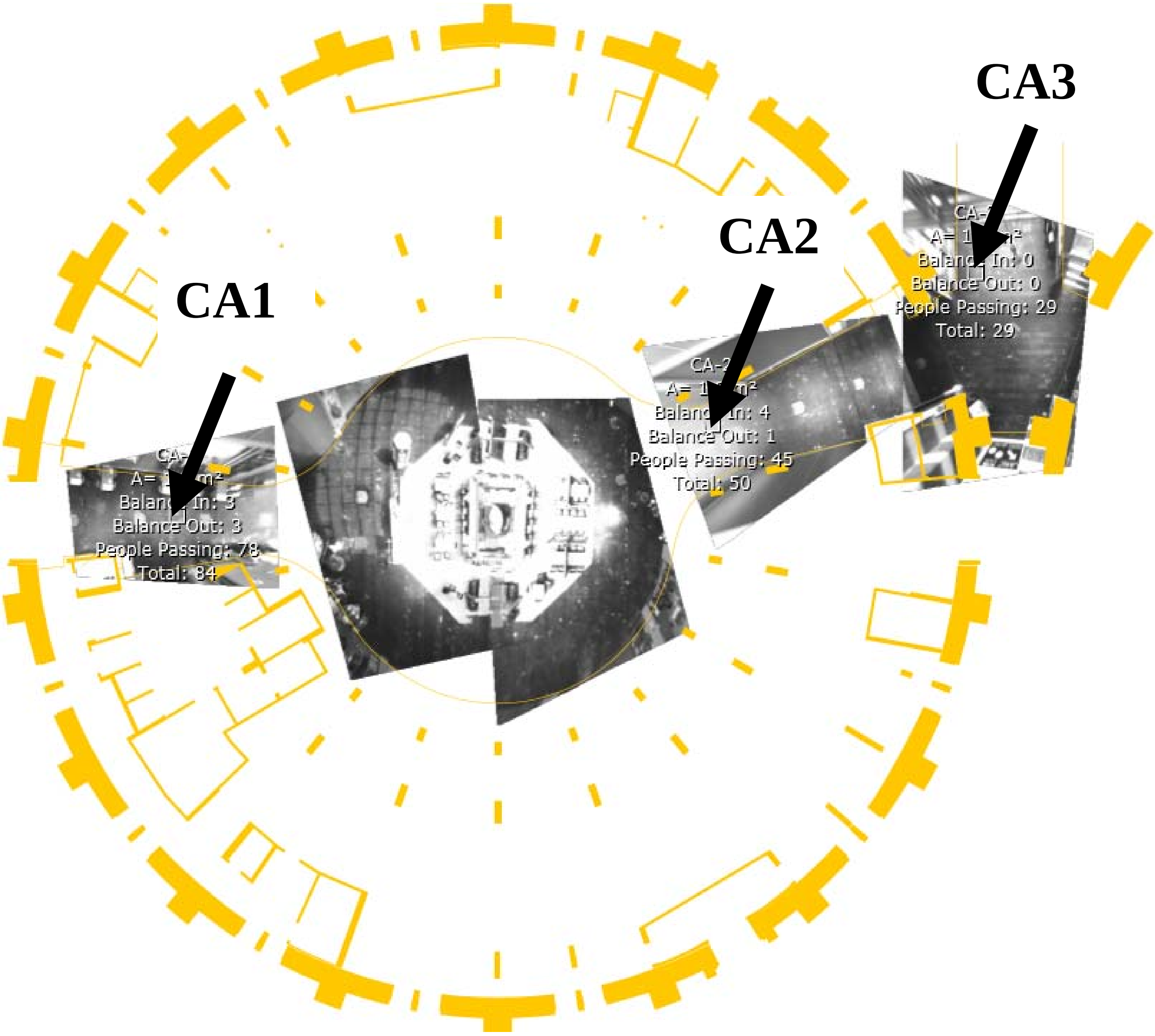


Fig. 1: CCB Analyser. The yellow lines indicate the outline of the Gasometer shopping centre; the grey areas are the background pictures showing floors and furniture; arrows point at the three counter areas.

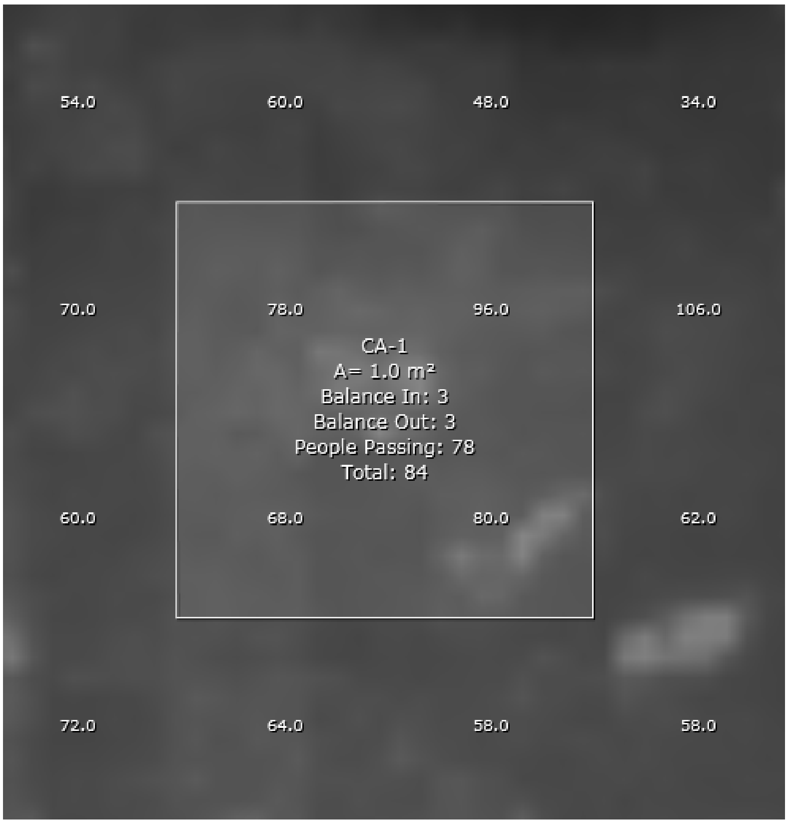


Fig. 2: Counter area 1 with values for frequency. Only the four values within the counter area were recorded.

The observation time can be chosen within the program, from a minimum of five minutes to a maximum of one day. All parameters are calculated for the desired time span and can thus be compared for different times. In this study the observed time span was always 30 minutes. For each day included in the data, three times were used – 08:30 to 09:00, 13:00 to 13:30 and 16:00 to 16:30 CET respectively CEST.

2.2. Variables

Not all measurements of the system were used for this study. The variables which were used are:

- *Total people passing*: Number of all people passing through the counter area within the observed time span.
- *Frequency*: Number of people per square meter during the observed time span.
- *Average speed*: Average speed of all people in m/s for the observed time span.
- *Average change of direction*: Average angle of direction change, including everyone who changed their direction for more than 10 and less than 90 degrees.
- *Number of direction changes*: Number of direction changes for more than 10 and less than 90 degrees during the observed time span.
- *Average speed decrease*: Average decrease of speed in m/s, including everyone who decreased their speed for more than 0.25m/s.
- *Number of speed decreases*: Number of speed decreases for more than 0.25 m/s during the observed time span.
- *Average speed increase*: Average increase of speed in m/s, including everyone who increased their speed for more than 0.25m/s.
- *Number of speed increases*: Number of speed increases for more than 0.25 m/s during the observed time span.

Since the main purpose of this study was to investigate the personal space of pedestrians, we had to find ways to measure violations of pedestrians' personal spaces. To do this two different approaches were used. The first one was named *personal space in circles* (from now on referred to as *PSC*): Around every person in one picture recorded by the sensors circles of different diameters were drawn. These circles represented different personal space areas around the person. When there was another person within these circles, points were added up depending on how close (e.g. within which circle) this person was. All the points for each person in each picture over the observed time span were added for each grid square. An example for this calculation is shown in Fig. 3.

Circle diameters and respective points:

5-10m = 1 point

1-5m = 2 points

<1m = 3 points

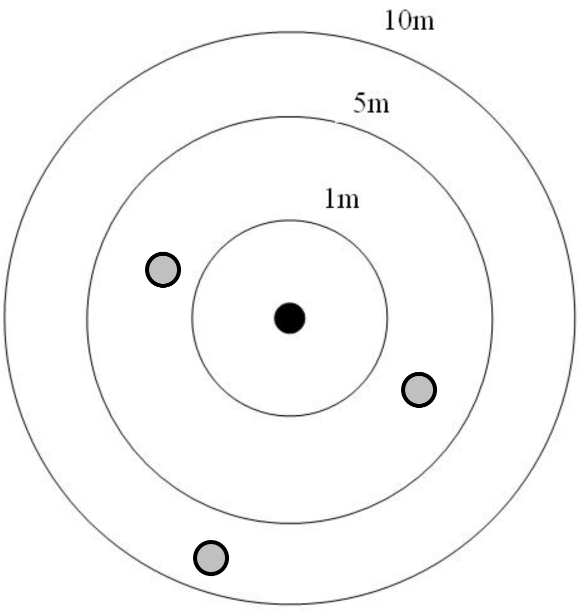


Fig. 3: Personal space in circles (PSC). The black dot marks a person, the circles around it the three different personal space distances. The grey dots mark other people located near the observed person. The calculation for the PSC value of this person would be: 2 + 2 + 1 = 5

The second approach included movements of the observed people. Based on Gérin-Lajoie et al.'s study (2007), a "house-shaped" personal space was chosen, being bigger 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, the program calculated the positions of this person in the next pictures, assuming that the person continued walking in the exact same direction as he/she did until then. If another person entered the first person's personal space within one of the next pictures, one point was added to the first person (see Fig. 4 for an example). This was done for every person in each picture, and all the points for each square grid and within the observed time span were added.

The size of the personal space could be enlarged without changing the shape or proportions. Also, the number of frames being calculated ahead could be changed.
Therefore, we calculated six different personal space values for this study:

1. Planning 2 frames (≙1 second) ahead with a personal space of 80cm to the sides and 160cm to the front. From now on referred to as PS2/small.
2. Planning 4 frames (≙2 seconds) ahead with a personal space of 80cm to the sides and 160cm to the front. From now on referred to as PS4/small.
3. Planning 6 frames (≙3 seconds) ahead with a personal space of 80cm to the sides and 160cm to the front. From now on referred to as PS6/small.
4. Planning 2 frames (≙1 second) ahead with a personal space of 120cm to the sides and 240cm to the front. From now on referred to as PS2/big.
5. Planning 4 frames (≙2 seconds) ahead with a personal space of 120cm to the sides and 240cm to the front. From now on referred to as PS4/big.

6. Planning 6 frames (≙3 seconds) ahead with a personal space of 120cm to the sides and 240cm to the front. From now on referred to as PS6/big.

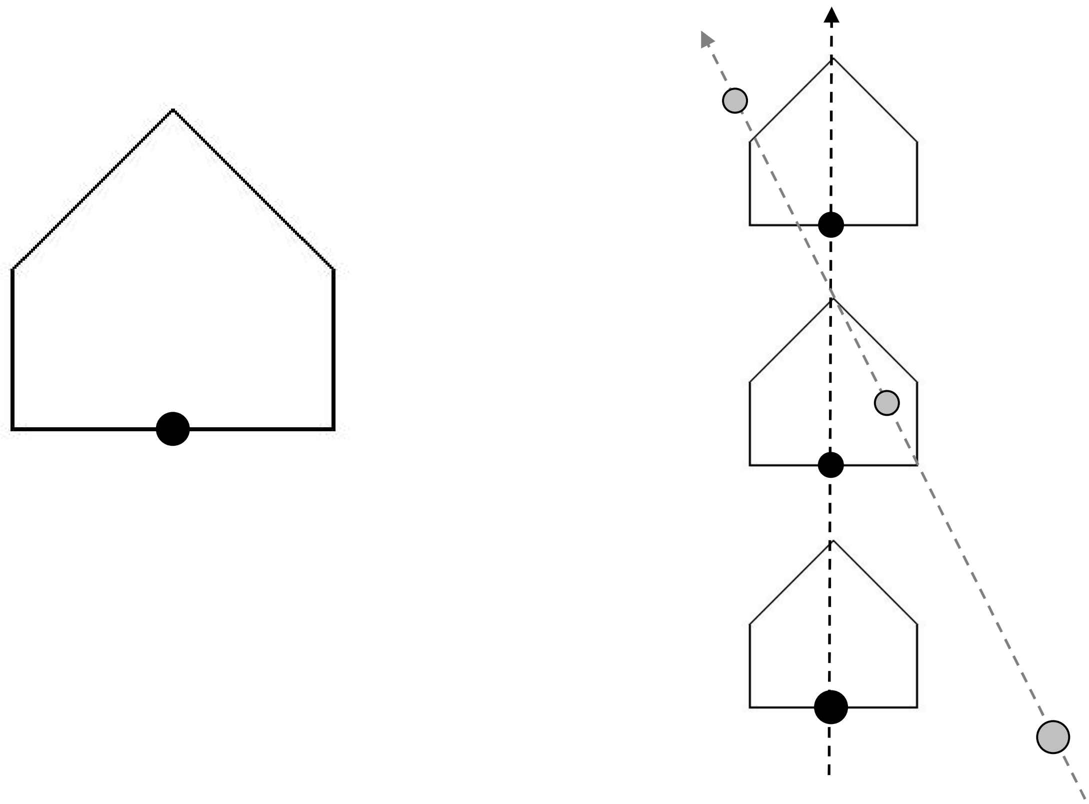


Fig. 4: Personal space in motion. The black dot marks the observed person. In the left picture the lines show the shape of the personal space, being bigger in the front and zero in the rear. The picture on the right shows a person at a given moment (bigger dot) with two positions/frames of the same person being calculated ahead (smaller dots). The gray 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.

2.3. Data

The data used for this study were recorded from the 22nd of June 2010 to the 13th of November 2010. There was no data used between the 15th of July 2010 and the 11th of October 2010, because one of the sensors did not work during that period.

Altogether, 507 datasets were recorded, including 19 variables each. Every set contains a 30 minute time span. For each day, 9 sets were recorded – at three different times and three different counter areas.

2.3.1. Data transformation. Since there were four values for each variable (excluding the total number of people passing the counter area) because of the four grid squares within the counter area and because many variables were dependent on the number of people, those variables had to be transformed: For *frequency*, the sum of the four values was calculated. For *average speed, average change of direction, average speed decrease* and *average speed increase* the average of the four values was calculated. For *number of direction changes, number of speed decreases* and *number of speed increases* the percentages of people changing direction or speed were calculated. For all personal space values the sums of the four values were calculated and then divided by the total number of people crossing the area.

III. RESULTS

3.1. Descriptive statistics

Altogether 15 210 minutes (= 10.56 days) of recordings were used for this study, divided into 30 minute sets. 66 sets were recorded on Mondays (13.0%), 81 on Tuesdays and Wednesdays (16.0% each), 72 on Thursdays, Fridays and Saturdays (14.2% each) and 63 on Sundays (12.4%). 168 sets were recorded in the morning and at midday (33.1% each), while 171 were recorded on afternoons (33.7%). Each counter area was recorded 169 times (33.3%).

On average 49.83 (range: 0-173; SD: 35.08) people were observed in each set. This makes altogether 25 265 observed people. The mean frequency (people per square meter) was 169.75 (range: 0-604; SD: 123.07). The average speed of the observed people was 1.71m/s (range: 0-3.28m/s; SD: 0.52). On average 15.1% (range: 0-100%; SD: 9.71) of the observed people decreased their speed, with an average speed decrease of 0.31m/s (range: 0-0.83m/s; SD: 0.17). 14.5% of the observed people increased their speed (range: 0-66.67%; SD: 8.81) with an average speed increase of 0.31m/s (range: 0-0.88m/s; SD: 0.16). The average direction change was 15.85 degrees (range: 0-43.25; SD: 7.98), with 29.66% of people changing their direction for more than 10 degrees.

The mean value for the circular personal space (PSC) was 1.95 (range: 0-8.34; SD: 1.51), for PS2/small 0.04 (range: 0-0.35; SD: 0.05), PS4/small (range: 0-0.63; SD: 0.09), for PS6/small 0.11 (range: 0-0.79; SD: 0.12), PS2/big 0.09 (range: 0-0.58; SD: 0.11), PS4/big 0.15 (range: 0-0.75; SD: 0.16), and for PS6/big 0.2 (range: 0-0.94; SD: 0.21).

3.2. Comparison of weekdays

When comparing weekdays almost no differences were found between workdays (Monday to Friday). The average direction change was higher on Tuesdays than on Mondays (Z=-2.071; p=0.038) and the average speed was higher on Tuesdays than on Thursdays (Z=-

2.159; p=0.031). All other differences were found between workdays and weekends (Saturday and Sunday); therefore further analysis was conducted comparing all workdays with weekends (Table 1). The total number of observed people and the frequency of people were higher on workdays (Fig.5), as were average speed, average speed decrease, average speed increase and average direction change. There were less invasions of circular personal space per person on weekends than during the week (Fig. 6).

There were no differences in the percentages of people changing direction or speed, and also in the six personal space values PS2/small to PS6/big.

Table 1: Comparison of weekdays (Monday to Friday) versus weekends (Saturday and Sunday).
Total = average total number of observed people per 30min. Fr = frequency of observed people per square meter. Speed = average walking speed. Angle = average angle of direction change. Angle% = percentage of people changing direction. SpeedDE = average speed decrease in m/s. SpeedDE% = percentage of people decreasing speed. SpeedIN = average speed increase in m/s. SpeedIN% = percentage of people increasing speed. PSC = circular personal space. PS2/small – PS6/big = personal space in motion (see above for detailed explanation).

	Weekdays (N=370)	Weekends (N=131)	Mann-Whitney U test	
	Median	Median	Z-Value	p-Value
Total	51.00	23.00	-8.529	<0.001
Fr	172.00	76.00	-8.366	<0.001
Speed	1.55	1.47	-4.474	<0.001
Angle	17.75	14.00	-5.163	<0.001
Angle%	26.97	29.79		n.s
SpeedDE	0.33	0.23	-5.777	<0.001
SpeedDE%	13.11	14.81		n.s
SpeedIN	0.33	0.23	-5.794	<0.001
SpeedIN%	13.22	13.33		n.s
PSC	1.56	1.25	-3.387	0.001
PS2/small	0.03	0.00		n.s
PS4/small	0.05	0.03		n.s
PS6/small	0.06	0.05		n.s
PS2/big	0.06	0.03		n.s
PS4/big	0.09	0.08		n.s
PS6/big	0.13	0.13		n.s

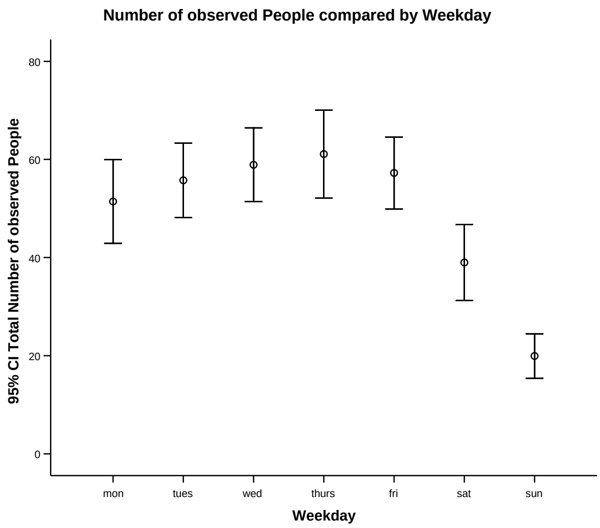


Fig. 5: Number of observed people compared by weekday. More people were observed during the workweek than on weekends.

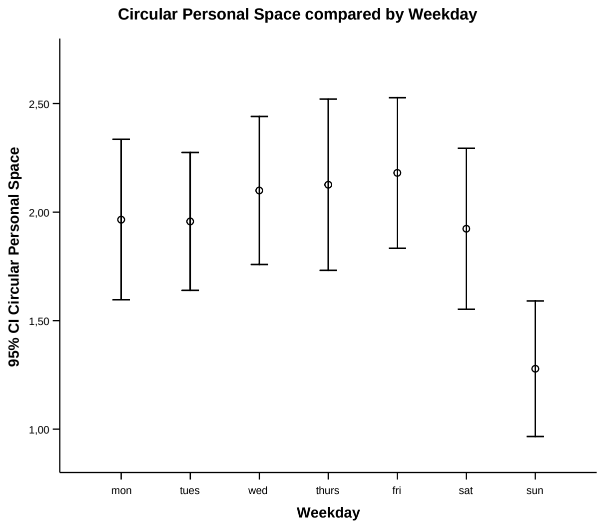


Fig. 6: Circular personal space compared by weekday. More violations of circular personal space occurred during the workweek than on weekends.

3.3. Comparison of times

The three observation times – 08:30 to 09:00, 13:00 to 13:30 and 16:00 to 16:30 – were compared (see Table 2). Analysis shows that there were great differences, especially when comparing morning to midday and afternoon. The total number of observed people and the frequency of people were lower in the morning than later during the day (Fig. 7). Average direction change, average speed decrease and average speed increase were also lower, as were the percentages of people decreasing their speed and changing direction. Personal space was less invaded in the morning (Fig. 8). There were no differences in the average speed and the percentage of people increasing their speed between morning, midday and afternoon.

There were more people observed during midday than in the afternoon and the average direction change and speed increase were higher. All other variables did not differ between midday and afternoon.

Table 2: Comparison of different times of day. Total = average total number of observed people per 30min. Fr = frequency of observed people per square meter. Speed = average walking speed. Angle = average angle of direction change. Angle% = percentage of people changing direction. SpeedDE = average speed decrease in m/s. SpeedDE% = percentage of people decreasing speed. SpeedIN = average speed increase in m/s. SpeedIN% = percentage of people increasing speed. PSC = circular personal space. PS2/small – PS6/big = personal space in motion (see above for detailed explanation).

				Mann-Whitney U test					
	08:30 (N=162)	13:00 (N=168)	16:00 (N=171)	08:30 / 13:00		08:30 / 16:00		13:00 / 16:00	
	Median	Median	Median	Z-Value	p-Value	Z-Value	p-Value	Z-Value	p-Value
Total	20.50	64.00	48.00	-10.987	<0.001	-9.512	<0.001	-4.036	<0.001
Fr	68.00	213.00	156.00	-10.768	<0.001	-9.134	<0.001	-3.948	<0.001
Speed	1.55	1.54	1.51		n.s.		n.s.		n.s.
Angle	11.63	19.13	16.75	-8.345	<0.001	-5.939	<0.001	-3.832	<0.001
Angle%	23.76	32.35	28.97	-3.952	<0.001	-2.399	0.016		n.s.
SpeedDE	0.18	0.35	0.35	-8.032	<0.001	-7.719	<0.001		n.s.
SpeedDE%	11.76	14.04	14.55	-2.135	0.033	-2.080	0.038		n.s.
SpeedIN	0.20	0.35	0.33	-7.786	<0.001	-6.380	<0.001	-2.345	0.019
SpeedIN%	12.50	13.65	13.21		n.s.		n.s.		n.s.
PSC	0.82	1.80	1.87	-8.961	<0.001	-8.153	<0.001		n.s.
PS2/small	0.00	0.03	0.03	-5.445	<0.001	-5.070	<0.001		n.s.
PS4/small	0.00	0.05	0.06	-5.626	<0.001	-5.065	<0.001		n.s.
PS6/small	0.03	0.08	0.08	-5.943	<0.001	-5.466	<0.001		n.s.
PS2/big	0.00	0.07	0.07	-6.482	<0.001	-5.867	<0.001		n.s.
PS4/big	0.03	0.12	0.10	-6.324	<0.001	-5.700	<0.001		n.s.
PS6/big	0.06	0.16	0.14	-6.600	<0.001	-5.896	<0.001		n.s.

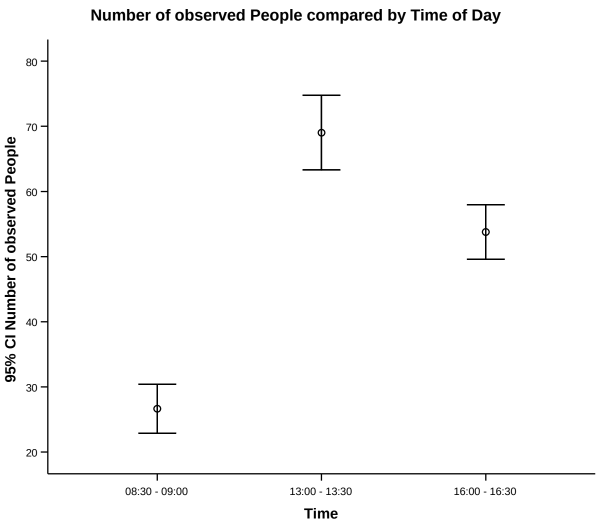


Fig. 7: Number of observed people compared by time of day. Least people were observed in the morning, most during midday.

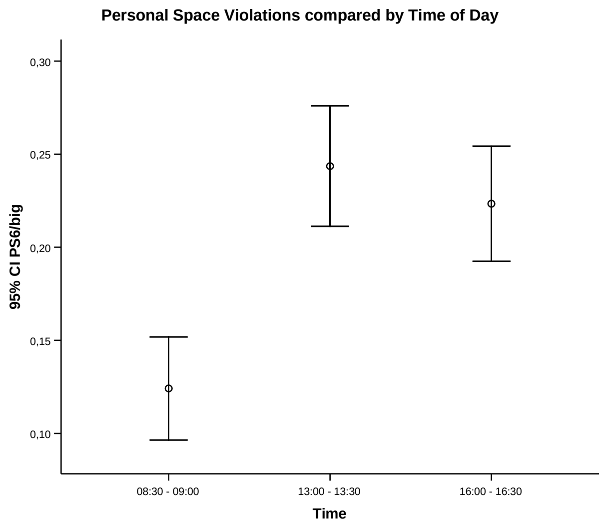


Fig. 8: Personal space (PS6/big) compared by time of day. Least violations of personal space occurred in the morning, most during midday.

3.4. Comparison of counter areas

Since the three counter areas were chosen for being different in terms of possible walking directions, all the variables were compared between them (see Table 3).

Every variable differed between counter areas 1 and 2. The total number of observed people and the frequency were higher in counter area 1 (Fig. 9), while average speed (Fig. 10), average speed decrease and average speed increase were lower, as were the percentages of people changing their speed. Average direction change and percentage of people changing direction were higher in counter area 1 than in counter area 2, and there were also more violations of personal space (Fig. 11).

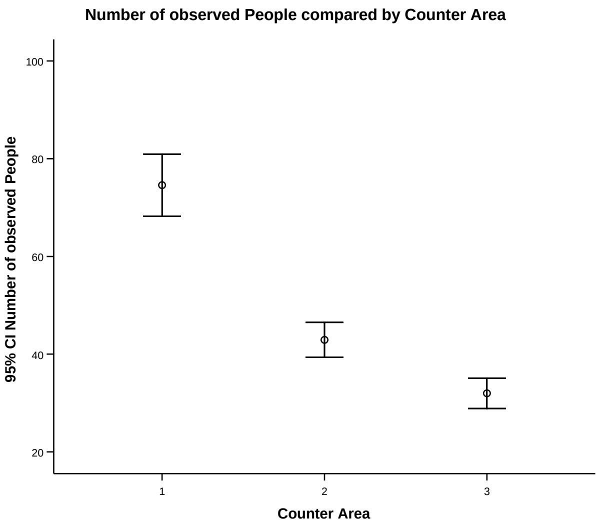
The total number of observed people (Fig. 9), the frequency and the average speed (Fig. 10) were higher in counter area 1 than in counter area 3.The average direction change and the percentage of people changing direction were lower. The average speed decrease was the same between the two counter areas, but the percentage of speed decreases was higher in counter area

3. Average speed increase and percentage of speed increases were both higher in counter area 1. There were more violations of personal space in counter area 1 than in counter area 3 (Fig. 11).

When comparing counter areas 2 and 3 the following differences were found: the total number of observed people and the frequency were higher in counter area 2 (Fig. 9), as were average speed (Fig. 10) and average speed decrease and increase. Also the percentage of people increasing their speed was higher. Average direction change and percentage of people changing direction were higher in counter area 3. Percentage of people decreasing their speed was the same for the two counter areas. There were more violations of circular personal space and of PS2/small in counter area 3, whereas the other personals space measures did not differ (Fig. 11).

Table 3: Comparison of the three counter areas. Total = average total number of observed people per 30min. Fr = frequency of observed people per square meter. Speed = average walking speed. Angle = average angle of direction change. Angle% = percentage of people changing direction. SpeedDE = average speed decrease in m/s. SpeedDE% = percentage of people decreasing speed. SpeedIN = average speed increase in m/s. SpeedIN% = percentage of people increasing speed. PSC = circular personal space. PS2/small – PS6/big = personal space in motion (see above for detailed explanation).

				Mann-Whitney U test					
	CA1 (N=168)	CA2 (N=169)	CA3 (N=164)	CA1 / CA2		CA1 / CA3		CA2 / CA3	
	Median	Median	Median	Z-Value	p-Value	Z-Value	p-Value	Z-Value	p-Value
Total	76.00	43.00	30.00	-7.247	<0.001	-9.710	<0.001	-4.360	<0.001
Fr	266.00	140.00	96.00	-8.286	<0.001	-10.270	<0.001	-4.023	<0.001
Speed	1.52	2.30	1.42	-14.008	<0.001	-7.186	<0.001	-14.531	<0.001
Angle	16.25	13.25	19.00	-2.520	0.012	-4.132	<0.001	-4.149	<0.001
Angle%	25.99	12.24	47.49	-9.523	<0.001	-12.191	<0.001	-14.051	<0.001
SpeedDE	0.30	0.45	0.28	-8.076	<0.001		n.s.	-8.291	<0.001
SpeedDE%	10.23	17.24	15.87	-8.853	<0.001	-7.976	<0.001		n.s.
SpeedIN	0.30	0.43	0.23	-7.819	<0.001	-3.012	0.003	-8.949	<0.001
SpeedIN%	10.41	16.67	13.33	-8.833	<0.001	-3.445	0.001	-4.509	<0.001
PSC	3.33	1.00	1.48	-12.472	<0.001	-9.446	<0.001	-6.087	<0.001
PS2/small	0.07	0.00	0.00	-11.106	<0.001	-9.195	<0.001	-2.131	0.033
PS4/small	0.17	0.02	0.02	-12.406	<0.001	-11.861	<0.001		n.s.
PS6/small	0.24	0.04	0.03	-12.806	<0.001	-12.703	<0.001		n.s.
PS2/big	0.18	0.03	0.03	-12.121	<0.001	-10.858	<0.001		n.s.
PS4/big	0.32	0.05	0.04	-13.059	<0.001	-12.653	<0.001		n.s.
PS6/big	0.43	0.08	0.07	-13.089	<0.001	-12.876	<0.001		n.s.



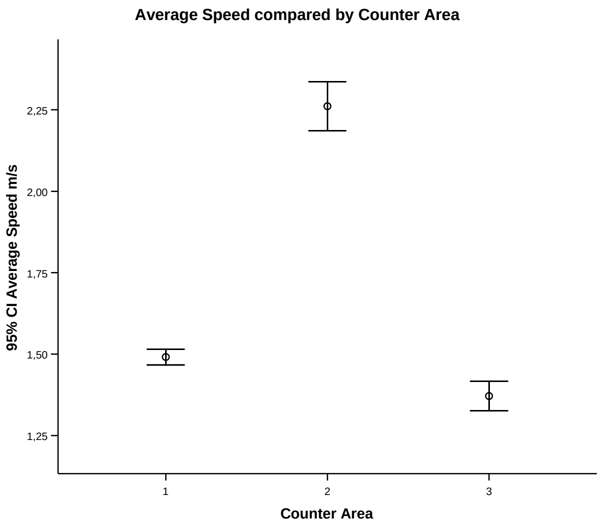


Fig. 9: Number of observed people compared by counter area. Most people were observed in counter area 1, least in counter area 3.

Fig. 10: Average speed compared by counter area. People were fastest in counter area 2.

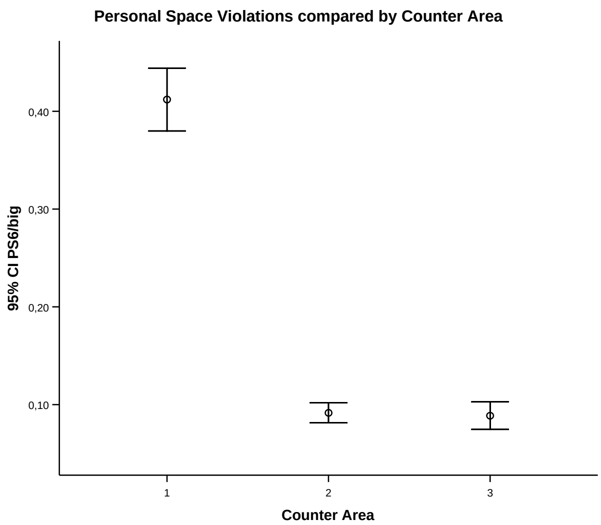


Fig. 11: Personal space (PS6/big) compared by counter area. Most violations of personal space occurred in counter area 1. There was no significant difference between counter areas 2 and 3.

3.5. Density

Density, measured by the number of observed people and the frequency of people, correlates with almost every other variable (Table 7). The more people there were at the same time the faster they walked (Fig. 12) and the more they changed direction and speed. There were also more violations of personal space at higher densities (Fig. 13).

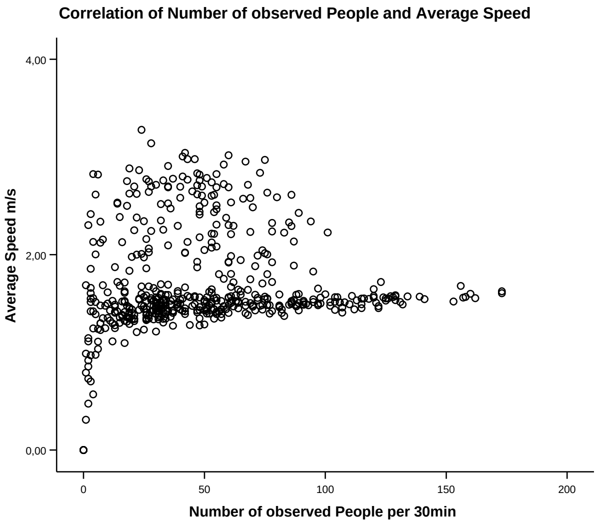


Fig. 12: Correlation of number of observed people and average walking speed. $r_s = 0.494$

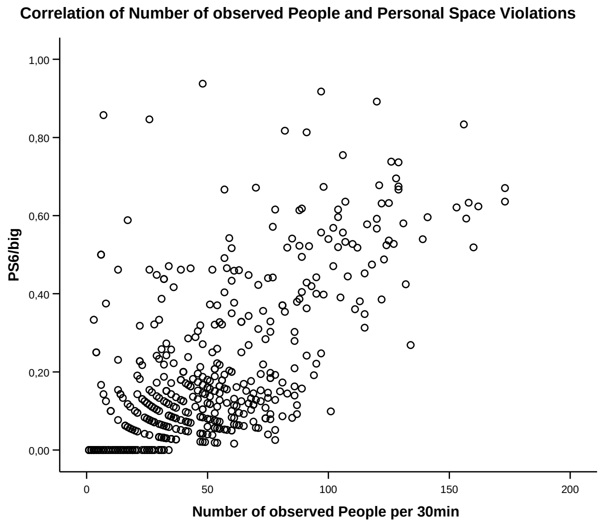


Fig. 13: Correlation of number of observed people and personal space violations (PS6/big). $r_s = 0.659$

3.6. Direction change

The average degree of change of direction correlates with every other variable except the percentage of people increasing their speed (Table 7). The average degree to which pedestrians changed their direction was higher with higher density (Fig. 14) and lower average walking speed. When higher direction changes occurred there were also more changes of walking speed and more violations of personal space.

The percentage of people changing their direction does not correlate with density. It was higher at lower walking speeds and when changes of speed were smaller. More people changed direction when the number of violations of circular personal space was higher (Fig. 15), but there was no correlation with personal space in motion (PS2/small – PS6/big).

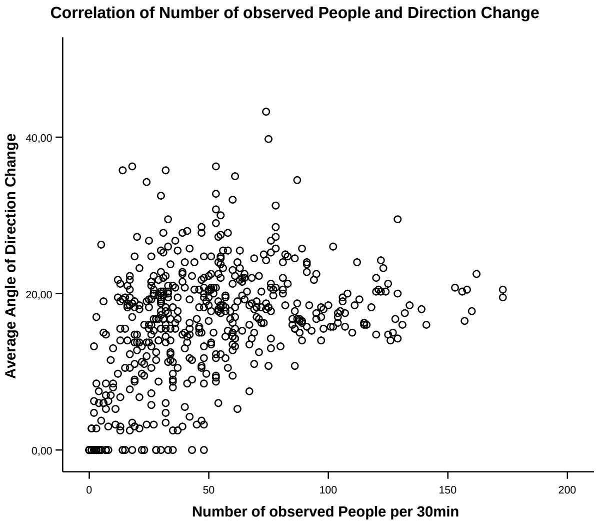


Fig. 14: Correlation of number of observed people and average angle of direction change. $r_s = 0.428$

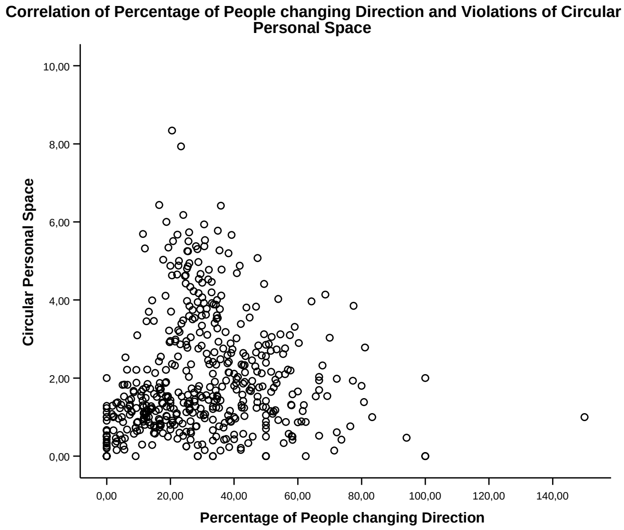


Fig. 15: Correlation of percentage of people changing direction and violations of circular personal space. $r_s = 0.230$

3.7. Speed

People walked faster at higher densities. There were smaller and less direction changes and bigger changes of speed at higher average walking speed. At higher speed there were less violations of circular personal space (Fig. 16). No correlations could be found with personal space in motion (PS2/small – PS6/big) (Table 7).

The average speed decrease and the average speed increase correlate positively with almost every other variable. The only exception is the percentage of people changing direction, which becomes smaller as changes of speed become bigger.

The percentage of people decreasing their speed correlates with every variable except for average speed. More people decreased their speed at lower densities and when there were less violations of personal space.

The percentage of people increasing their speed correlates with every variable except for the number of observed people, frequency, average change of direction, and percentage of people changing direction. It shows the same pattern as the percentage of people decreasing their speed, being bigger when less violations of personal space occur. The changes of direction and speed including the degree of changes and the percentage of people changing their walking behavior all correlate positively.

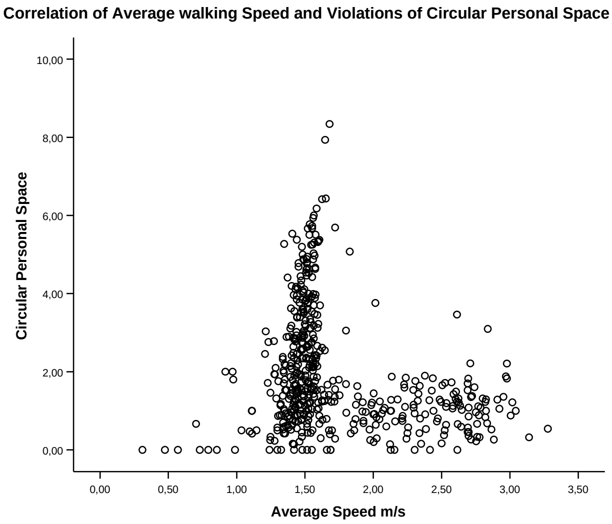


Fig. 16: Correlation of average walking speed and violations of circular personal space. $r_s = -0.150$

Since average speed was higher in counter area 2 than in the other counter areas (Fig. 10), all correlations were calculated excluding counter area 2 (Table 5). In this analysis average speed correlated with every variable – including number of observed people (Fig. 17) and all the personal space values (Fig. 18) – except for the average direction change and the percentage of people increasing their speed.

Table 5: Correlation of average walking speed, excluding counter area 2. Total = average total number of observed people per 30min. Fr = frequency of observed people per square meter. Speed = average walking speed. Angle = average angle of direction change. Angle% = percentage of people changing direction. SpeedDE = average speed decrease in m/s. SpeedDE% = percentage of people decreasing speed. SpeedIN = average speed increase in m/s. SpeedIN% = percentage of people increasing speed. PSC = circular personal space. PS2/small – PS6/big = personal space in motion (see above for detailed explanation).

			Total	Fr	Speed	Angle
Spearman's rho	Speed	Correlation Coefficient	0.494	0.502	1.000	-0.012
		Sig. (2-tailed)	<0.001	<0.001	.	0.822
		N	338	338	338	338
			Angle%	**SpeedDE**	**SpeedDE%**	**SpeedIN**
	Speed	Correlation Coefficient	-0.480	0.293	-0.190	0.282
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001
		N	332	338	332	338
			SpeedIN%	**PSC**	**PS2/small**	**PS4/small**
	Speed	Correlation Coefficient	-0.092	0.388	0.386	0.378
		Sig. (2-tailed)	0.095	<0.001	<0.001	<0.001
		N	332	332	332	332
			PS6/small	**PS2/big**	**PS4/big**	**PS6/big**
	Speed	Correlation Coefficient	0.369	0.403	0.406	0.389
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001
		N	332	332	332	332

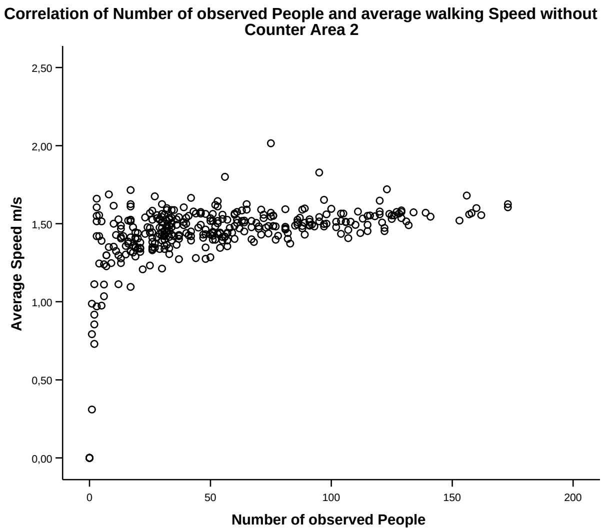


Fig. 17: Correlation of number of observed people and average walking speed. $r_s = 0.494$. Counter Area 2 was excluded, because of the unusually high average walking speed that was measured there.

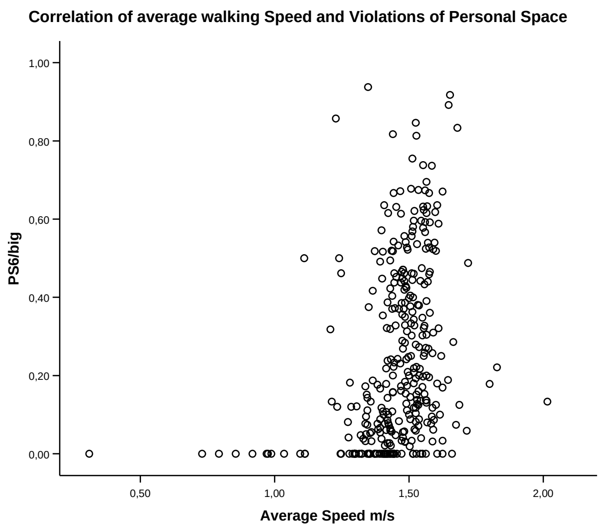


Fig. 18: Correlation of average walking speed and violations of personal space (PS6/big). $r_s = 0.389$. Counter Area 2 was excluded, because of the unusually high average walking speed that was measured there.

Speed and the personal space values were also correlated partially, controlling for the total number of people observed. Here, average speed correlated negatively with every personal space value (Table 6).

Table 6: Partial correlation of average walking speed with personal space, controlling for number of people. Total = average total number of observed people per 30min. Speed = average walking speed. PSC = circular personal space. PS2/small – PS6/big = personal space in motion (see above for detailed explanation).

Control Variables			PSC	PS2/small	PS4/small	PS6/small
Total	Speed	Correlation Coefficient	-0.430	-0.189	-0.252	-0.261
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001
		df	498	498	498	498
			PS2/big	PS4/big	PS6/big	
	Speed	Correlation Coefficient	-0.236	-0.269	-0.267	
		Sig. (2-tailed)	<0.001	<0.001	<0.001	
		df	498	498	498	

3.8. Personal space

Circular personal space (PSC) correlates with every other variable (Table 7). More violations occurred at higher density and lower speed. The more violations of circular personal space occurred the more people changed walking direction, and there were less but bigger changes of speed. The six other personal space values (PS2/small – PS6/big) show the same pattern, but do not correlate with average speed and percentage of people changing direction.

Table 7: Correlations of all variables. Total = average total number of observed people per 30min. Fr = frequency of observed people per square meter. Speed = average walking speed. Angle = average angle of direction change. Angle% = percentage of people changing direction. SpeedDE = average speed decrease in m/s. SpeedDE% = percentage of people decreasing speed. SpeedIN = average speed increase in m/s. SpeedIN% = percentage of people increasing speed. PSC = circular personal space. PS2/small – PS6/big = personal space in motion (see above for detailed explanation).

			Total	Fr	Speed	Angle	Angle%	SpeedDE	SpeedDE%	SpeedIN	SpeedIN%
Spearman's rho	Total	Correlation Coefficient	1.000	0.994	0.231	0.428	-0.045	0.530	-0.113	0.548	-0.073
		Sig. (2-tailed)	.	<0.001	<0.001	<0.001	0.314	<0.001	0.012	<0.001	0.101
		N	507	507	507	507	501	507	501	507	501
	Fr	Correlation Coefficient	0.994	1.000	0.207	0.423	-0.032	0.507	-0.122	0.528	-0.081
		Sig. (2-tailed)	<0.001	.	<0.001	<0.001	0.475	<0.001	0.006	<0.001	0.069
		N	507	507	507	507	501	507	501	507	501
	Speed	Correlation Coefficient	0.231	0.207	1.000	-0.144	-0.690	0.465	0.037	0.482	0.211
		Sig. (2-tailed)	<0.001	<0.001	.	0.001	<0.001	<0.001	0.411	<0.001	<0.001
		N	507	507	507	507	501	507	501	507	501
	Angle	Correlation Coefficient	0.428	0.423	-0.144	1.000	0.484	0.380	0.218	0.323	0.087
		Sig. (2-tailed)	<0.001	<0.001	0.001	.	<0.001	<0.001	<0.001	<0.001	0.053
		N	507	507	507	507	501	507	501	507	501
	Angle%	Correlation Coefficient	-0.045	-0.032	-0.690	0.484	1.000	-0.133	0.186	-0.189	-0.045
		Sig. (2-tailed)	0.314	0.475	<0.001	<0.001	.	0.003	<0.001	<0.001	0.311
		N	501	501	501	501	501	501	501	501	501
	SpeedDE	Correlation Coefficient	0.530	0.507	0.465	0.380	-0.133	1.000	0.443	0.636	0.189
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	0.003	.	<0.001	<0.001	<0.001
		N	507	507	507	507	501	507	501	507	501
	SpeedDE%	Correlation Coefficient	-0.113	-0.122	0.037	0.218	0.186	0.443	1.000	0.107	0.131
		Sig. (2-tailed)	0.012	0.006	0.411	<0.001	<0.001	<0.001	.	0.017	0.003
		N	501	501	501	501	501	501	501	501	501
	SpeedIN	Correlation Coefficient	0.548	0.528	0.482	0.323	-0.189	0.636	0.107	1.000	0.484
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.017	.	<0.001
		N	507	507	507	507	501	507	501	507	501
	SpeedIN%	Correlation Coefficient	-0.073	-0.081	0.211	0.087	-0.045	0.189	0.131	0.484	1.000
		Sig. (2-tailed)	0.101	0.069	<0.001	0.053	0.311	<0.001	0.003	<0.001	.
		N	501	501	501	501	501	501	501	501	501

			PSC	PS2/small	PS4/small	PS6/small	PS2/big	PS4/big	PS6/big
Spearman's rho	Total	Correlation Coefficient	0.749	0.559	0.591	0.608	0.631	0.653	0.659
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	Fr	Correlation Coefficient	0.769	0.580	0.615	0.634	0.655	0.680	0.686
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	Speed	Correlation Coefficient	-0.150	-0.022	-0.030	-0.007	-0.014	-0.004	0.018
		Sig. (2-tailed)	0.001	0.620	0.505	0.873	0.760	0.936	0.694
		N	501	501	501	501	501	501	501
	Angle	Correlation Coefficient	0.395	0.224	0.190	0.170	0.231	0.202	0.195
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	Angle%	Correlation Coefficient	0.230	0.066	0.008	-0.023	0.057	0.009	-0.014
		Sig. (2-tailed)	<0.001	0.139	0.859	0.606	0.205	0.834	0.754
		N	501	501	501	501	501	501	501
	SpeedDE	Correlation Coefficient	0.223	0.161	0.137	0.137	0.182	0.177	0.180
		Sig. (2-tailed)	<0.001	<0.001	0.002	0.002	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	SpeedDE%	Correlation Coefficient	-0.133	-0.169	-0.217	-0.220	-0.190	-0.218	-0.213
		Sig. (2-tailed)	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	SpeedIN	Correlation Coefficient	0.206	0.117	0.102	0.136	0.157	0.154	0.172
		Sig. (2-tailed)	<0.001	0.009	0.023	0.002	<0.001	0.001	<0.001
		N	501	501	501	501	501	501	501
	SpeedIN%	Correlation Coefficient	-0.183	-0.171	-0.184	-0.186	-0.152	-0.174	-0.183
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501

			PSC	PS2/small	PS4/small	PS6/small	PS2/big	PS4/big	PS6/big
Spearman's rho	PSC	Correlation Coefficient	1.000	0.715	0.717	0.725	0.788	0.780	0.777
		Sig. (2-tailed)	.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	PS2/small	Correlation Coefficient	0.715	1.000	0.875	0.812	0.879	0.822	0.776
		Sig. (2-tailed)	<0.001	.	<0.001	<0.001	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	PS4/small	Correlation Coefficient	0.717	0.875	1.000	0.939	0.858	0.927	0.883
		Sig. (2-tailed)	<0.001	<0.001	.	<0.001	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	PS6/small	Correlation Coefficient	0.725	0.812	0.939	1.000	0.840	0.919	0.940
		Sig. (2-tailed)	<0.001	<0.001	<0.001	.	<0.001	<0.001	<0.001
		N	501	501	501	501	501	501	501
	PS2/big	Correlation Coefficient	0.788	0.879	0.858	0.840	1.000	0.930	0.888
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	.	<0.001	<0.001
		N	501	501	501	501	501	501	501
	PS4/big	Correlation Coefficient	0.780	0.822	0.927	0.919	0.930	1.000	0.962
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	<0.001	.	<0.001
		N	501	501	501	501	501	501	501
	PS6/big	Correlation Coefficient	0.777	0.776	0.883	0.940	0.888	0.962	1.000
		Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	.
		N	501	501	501	501	501	501	501

IV. DISCUSSION

The goal of this study was to find out more about human walking behavior, especially about the effect of high density and intrusion into personal space on speed and direction change. Pedestrians were observed and a computer program called CCB Analyser calculated averages for speed, density, change of speed, change of direction and two different approaches to personal space invasions, one being the personal space represented by circles around a person in single frames and the other one being calculated ahead dependent on the paths people were walking.

Results show that almost all variables depend on each other. A reason for that could be one main factor influencing most of the variables – most probably the total number of people. Even when accounting for it by dividing the variables by the number of observed people or calculating percentages, these influences persist. The more people there are the higher the density and therefore the more intrusions into personal space can occur.

4.1. Comparison of weekdays

When comparing weekdays most differences were found between workdays and weekends. The stores of the Gasometer are closed on Sundays as are the many office buildings surrounding it. There might be completely different people walking through the building on weekends, who for example visit the cinema located in Gasometer E or the fitness studio in Gasometer D. Also, fewer people were observed on weekends than during the workweek. They walked slower and there were less invasions of circular personal space. What is remarkable is that although the same percentage of people changed their direction and speed, those changes themselves were bigger during the workweek, indicating that in higher densities not more people change direction and speed, but that instead the people who do change it to a greater degree.

4.2. Comparison of times

There were big differences in walking behavior between morning, midday and afternoon. Most people were observed during midday, least in the morning. Almost every measured parameter was higher during midday than in the morning, including direction change (percentage and degree), speed decrease (percentage and degree), speed increase (degree) and all personal space values. Contrary to the theory of number of people being the main factor influencing all other variables there were almost no other differences between midday and afternoon, although the number of observed people per 30min differed significantly.

4.3. Comparison of counter areas

When comparing the three counter areas it shows that there wore more people walking through counter area 1 than through counter areas 2 and 3 combined. Because of the high density all personal space variables have higher values in this counter area. Direction change (percentage and degree) was biggest in counter area 3. This can be explained by its location, lying within a crossing of three hallways, which might force pedestrians to change their walking direction. All variables concerning speed were highest in counter area 2. This includes average walking speed, which was at 2.30m/s much higher than described in the literature (e.g. Bohannon, 1997; Costa, 2010; Henderson and Lyons, 1972; Vallis and McFadyen, 2003). Speed decrease (percentage and degree) and speed increase (percentage and degree) were also higher in this area. It is still unclear if people really walked that much faster in this area or if there was a technical problem, for example caused by the angle of the sensor.

4.4. Density

Density, measured by the number of observed people within each 30min set and the frequency of people per square meter, correlated with almost every other variable. Confirming my hypotheses, people walked faster at higher densities, changed their direction and speed to greater degrees and violated each others personal space more often. However, a smaller percentage of people decreased their speed in high density situations and there were no correlations for the percentage of people increasing their speed and changing direction. This suggests that although the number of people who have to change their walking behavior when many others are around is the same or even smaller, the degree to which those people change their walking behavior is bigger (e.g. Gérin-Lajoie et al., 2006; Gérin-Lajoie et al., 2008; Konečni et al., 1975).

4.5. Direction change

The average angle to which walking direction was changed correlated with most other variables. Supporting the second hypothesis, namely that higher density leads to more direction changes, the angle of direction change increased with increasing density and more violations of personal space. As mentioned above there was no correlation between density and the percentage of people who changed direction, indicating that at higher densities the same number of people change walking direction as at lower densities, but do so to a greater degree.

People who walked slower changed their direction on average more often and to a greater degree, which makes sense considering that step length needs to be reduced when not walking straight, thus automatically reducing speed (Chung and Hahn, 1999; Patla, 1996).

We also found that more people changed their direction when the number of violations of circular personal space was higher, but not when more violations of personal space in motion (PS2/small – PS6/big) occurred. However, as with density, the angle to which people changed their direction was bigger at higher values for PS2/small – PS6/big.

4.6. Speed

Average speed correlated with the total number of pedestrians, showing that although people try to keep their desired walking speed whenever it is possible (Helbing et al., 2001; Ralston, 1958) they still have to change it depending on how many others there are. Nevertheless there was no correlation between walking speed and personal space intrusions. Mean walking speed in this sample was with 1,71m/s slightly higher than described in literature (e.g. Bohannon, 1997; Costa, 2010; Henderson and Lyons, 1972; Vallis and McFadyen, 2003). However, this was mainly due to the very high average speed (2.30m/s) in counter area 2. It is unclear if this was a measuring error because of a technical problem of the system or if people really walked faster in this area. In counter areas 1 and 3 average speeds laid within the described ranges (1.49m/s for counter area 1 and 1.37m/s for counter area 3). Therefore, correlations were also calculated excluding counter area 2. This analysis showed different results, namely that average speed and possible personal space intrusions did in fact depend on each other, confirming hypothesis 1 that walking speed increases with higher density because of stress (Konečni et al., 1975). There was no situation where density was so high that people could not move freely and therefore had to decrease their speed.

When controlling for the number of observed people average speed of all three counter areas and intrusions into personal space also correlated negatively, adding support for hypothesis 1.

4.7. Personal space

The main goal of this study was to find out more about the personal space of pedestrians – how they react to intrusions and how they try to avoid them. Therefore two ways of measuring personal space violations were created; one being circular personal space around each person, the other one being possible personal space collisions calculated by the paths people were going, which was measured in six different sizes. In this study those two approaches brought very similar results. Circular personal space correlated with every other variable. The six personal space in motion values correlated with every variable except for the percentage of people changing direction. However, they only correlated with the average walking speed if either the very high average speed in counter area 2 was excluded or the analysis was controlled for the number of observed people. As already mentioned, more violations of personal space occurred when there were more people and at lower walking speed. Also changes of speed and walking direction were bigger when personal space was violated more often. However the percentage of people changing speed was lower at the same time and the percentage of people changing direction did not correlate with personal space. This shows that when there are more violations of personal space less people change speed (Konečni et al., 1975) and the same number of people changes direction (e.g. Gérin-Lajoie et al., 2006; Gérin-Lajoie et al., 2008), but they do so to a greater degree.

Although these results are very interesting and help to increase knowledge about human walking behavior, it is unfortunate that there were no bigger differences between the individual personal space values, especially the six values of personal space in motion. Since this was the first time attempting a calculation like this and there was not much literature available it is possible that the distances to the sides and to the front that were chosen were too big to show a significant effect when making them bigger. Also a maximum of three seconds of planning one's walking path ahead was used in this study, but it is likely that people planned their paths further ahead, so that adaptations of walking behavior were the same for every distance within those three seconds. It would be very interesting to conduct follow up studies with more extreme differences for those values, to maybe find the point at which pedestrians start changing their paths according to density, and the point at which they stop doing so.

4.8. CCB Analyser – future implications

The Viennese company Yellowfish GmbH developed the CCB Analyser over the last years. It is used to monitor crowded public places like train stations or shopping malls, without invading people's privacy. The CCB Analyser only shows the movement of crowds, thus making it impossible to identify individual people or to follow somebody's path through the observed area. Therefore it can be used almost everywhere without violating privacy laws.

One part of the present study was to help creating the tools to measure personal space. Since there has never been a similar approach to this and there is almost no literature about the personal space of pedestrians it is a very new way to study this topic. As the results show it still needs some improvement and experimentation, especially regarding the size of personal space and the time people plan their paths ahead. Also, there might be many other things that can be measured with CCB Analyser that have not been considered yet, which makes it a great tool for scientific study about pedestrian behavior in general.

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ZUSAMMENFASSUNG

Menschen haben ein natürliches Bedürfnis, bestimmte physische Abstände zueinander einzuhalten. Diese Distanzen nennt man *Personal Space* (oder *Personal Distance*). Edward T. Hall (1966) beschrieb sie als eine Distanz von 45 bis 120cm, die zwischen zwei Menschen eingehalten wird. Sie können einander berühren, wenn sie die Arme ausstrecken und sehen einander klar, wenn auch nicht vollständig. Dieser Abstand wird immer zu Fremden gehalten, jedoch können bekannte Personen je nach der Beziehung zwischen beiden näher kommen. Wird der *Personal Space* ohne Zustimmung betreten kommt es zu physiologischen Reaktionen wie erhöhtem Puls, Schwitzen und erhöhtem Blutdruck (Middlemist and Knowles, 1976). Wir fühlen uns einfach unwohl wenn andere zu nahe kommen.

Personal Space wurde hauptsächlich für stehende und sitzende Testpersonen untersucht (z.B. Newman and Pollack, 1973; Thompson et al., 1979; Hayduk and Mainprize, 1980; Hayduk, 1981; Strube and Werner, 1984; Evans and Wener, 2007; Robson, 2008), nicht jedoch für gehende. Gérin-Lajoie und seine Kollegen (Gérin-Lajoie et al., 2006; Gérin-Lajoie et al., 2008) beschrieben eine Minimaldistanz, die Fußgänger zu stationären und sich bewegenden Hindernissen halten. Diese wurden als Grundlage für die vorliegende Studie verwendet. Mit Hilfe eines neuen Systems namens CCB Analyser wurde das Verhalten von Fußgängern in einem österreichischen Einkaufszentrum untersucht. Dabei wurden Daten zur Anzahl und Frequenz der Menschen, Durchschnittsgeschwindigkeit, Änderungen von Geschwindigkeit und Anzahl dieser Änderungen, Änderungen der Gehrichtung und Anzahl dieser Änderungen, und zwei verschiedene Ansätze zu Messung von *Personal Space* aufgenommen. Eine davon beinhaltete die Messung des *Personal Space* in Kreisen um Einzelaufnahmen von Personen, die zweite eine Messung der *Personal Space* für Fußgänger, die ihre Wege vorausplanen.

Die getestete Hypothese lautete, dass hohe Dichte und geringe Distanzen das Gehverhalten beeinflussen, indem die Geschwindigkeit aufgrund von Stress ansteigt (Konečni et al., 1975) und Gehgeschwindigkeit und Gehrichtung öfter geändert werden müssen. Die Ergebnisse der vorliegenden Studie zeigen, dass alle gemessenen Variablen stark voneinander abhängen. Wir konnten die Hypothese, dass Menschen schneller gehen wenn ihnen andere zu nahe kommen, zumindest teilweise bestätigen. Fußgänger ändern ihre Geschwindigkeit und Gehrichtung mehr bei hoher Dichte, jedoch bleibt der Prozentsatz der Menschen, die ihr Gehverhalten ändern, gleich oder sinkt sogar.

Diese Ergebnisse sollen einen ersten Einblick in das Verhältnis zwischen menschlichem Gehverhalten und *Personal Space* bieten, jedoch muss zu diesem Thema noch viel Forschung betrieben werden.

ABSTRACT

Humans have a natural desire to keep a certain physical distance from other humans. This distance is called personal space (or personal distance). Edward T. Hall (1966) describes it as a distance of 45 to 120cm kept from each other, a which people can touch if they extend their arms and see each other clearly, but not as a whole. Humans always try to keep this minimum distance to strangers, but might let familiar people closer, depending on their relationship. If personal space is invaded without consent it comes to physical reactions such as increased heart rate, sweating and increased blood pressure (Middlemist and Knowles, 1976). We simply feel uncomfortable when others come too close.

Personal space is well described for standing and seated test subjects (e.g. Newman and Pollack, 1973; Thompson et al., 1979; Hayduk and Mainprize, 1980; Hayduk, 1981; Strube and Werner, 1984; Evans and Wener, 2007; Robson, 2008), but not for walking people. Gérin-Lajoie and his colleagues (Gérin-Lajoie et al., 2006; Gérin-Lajoie et al., 2008) described minimum distances that pedestrians keep from stationary and moving obstacles, which were used as a basis for this study. Using a newly developed system called CCB Analyser the walking patterns of pedestrians in an Austrian shopping center were recorded. Data included number and frequency of people, average speed, speed changes and number of speed changes, direction changes and number of direction changes, and two different measures for personal space, one being personal space in circles around stationary recording frames and the other being personal space for pedestrians that plan their paths ahead.

The tested hypothesis was that high density and low interpersonal distance leads to a change of walking behavior – increasing walking speed because of stress (Konečni et al., 1975) and making people change their speed and directions when walking. The results of the present study show that all measured variables seem to highly depend on each other. We could at least partly confirm the hypothesis of people walking faster when personal space is

invaded. People changed their walking speed and direction to a higher degree at high densities, however the percentage of people changing their walking behavior was the same or even smaller.

These results offer a first insight into the relationship of human walking behavior and personal space, but much more research needs to be done on this topic.

Curriculum vitae

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