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Article

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Research Article

Pedestrian dynamics on narrow pavements in high-density Hong Kong

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ABSTRACT

Introduction: The investigation of pedestrian dynamics is important as cities continue to develop facilities for high volume foot traffic. Important insights into speed-density relationships, flow patterns, boundary effects and critical states have been derived from experimental studies. Extending these studies to real settings enables us to see how these relationships apply in settings with heterogeneous populations, complex trip purposes and undirected spatial behaviours. Hong Kong offers the opportunity to examine pedestrian dynamics in conditions of relatively dense pedestrian traffic on narrow pavements.
Methods: Data were collected from a sample of 24 street environments, varying in pavement width and pedestrian flow. Individual trajectories of 356 randomly selected individuals were extracted from video records. Pedestrian speed was related to the following independent variables: pedestrian volume, pavement width, effective width and shops. Speed was also related to lateral displacement and position. Lane formation and counterflows were measured. To examine how the street environment compares with the free-flow conditions of wider, dedicated corridors, speed was measured for 356 randomly selected individuals on 7 corridors in the mass transit rail (MTR) system.
Results: Displacement, effective width, number of shops and sex of the individual account collectively for 13.7% of variance in speed, while pedestrian volume was not significant. There is a slight tendency to righthand movement in bi-directional flows, with the rate of counterflow negatively related to dominant flow density.
Conclusions: Walking speed on Hong Kong streets is constrained by shopping activity, obstacles and reduced spatial dimensions. Walking speed is maintained through lateral displacement, with higher speeds at the outer edge of the bounded space. People walk significantly faster in unconstrained conditions of the MTR.

1. Introduction

The literature on pedestrian movement dynamics has burgeoned in recent years. Evacuation behaviour dominates this literature, in keeping with the need to better understand and avoid the disastrous consequences of panicked movement, such as occurred in 2010 at the Love Parade in Berlin (Lian et al., 2017), during the Hajj in Mecca in 2015, or the 2015 Spring Festival in Shanghai. Studies have been concerned with the dynamics of large crowd movement, bottlenecks and wayfinding in emergency situations. Also prominent in the literature are studies from the mass transport environment, where the facilities are bounded, complex in layout and subject to recurrent dense flows of people. A third area of interest in the literature is modelling of movement under various constraints. Pedestrian

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movement is notoriously complex, inspiring a whole generation intent on models that simulate various aspects of human movement behaviour. Given that safety and lives are at stake in these situations, it is reasonable that researchers have focussed so much on these fields of investigation.

Less investigated are the everyday spaces of movement in the city, especially the outdoor walking environment. Crowded and complex flows in confined public walkways have received relatively little attention except in experimental studies. The experimental studies reviewed below control the physical variables, subjects and behaviour protocols, revealing the salience of certain physical conditions on observed walking speed and flow density. While controlled experiments provide definitive results on individual factors in the behavioural outcome, the experimental approach for combining several variables is extremely onerous, if not impossible. In the real environment, as shown below, coping behaviours modify the expected outcome. Finally, also as shown in the literature, subjects and behavioural intentions are important in outcomes and cannot easily be simulated. For all these reasons, this study uses a cross-sectional research design to study the speed-density relationship in the real walking environment.

Hong Kong is a particularly suitable case for investigating flow-density relationships because it is built to extremely high density and has streets that are relatively narrow. Pavements are also narrow and typically constrained by fences introduced to the street environment in the 1970s to keep pedestrians off motor traffic lanes. Pedestrian flows are also among the highest in the world in such typical, outdoor walking environments. In our sample of 24 locations, 40% of recorded pedestrian densities exceeded 0.2 p/m^2. This is substantially greater than the flows measured in other very high flow situations worldwide. For example, the central part of the Ginza in Tokyo has peak density around 0.07 (2007). Density on rue Berger in front of Les Halles in Paris is 0.13 at peak flows, while those on the Kalverstraat in Amsterdam reach 0.19 (author's counts). If there are significant relationships between effective pavement width, pedestrian flow and velocity, we should uncover them here in the particularly dense, high flow conditions of Hong Kong.

In this paper, we take the microscopic approach to understand how individuals behave naturalistically in the environment, while considering effective width, variable walking velocity, the density of entrances to shops and simultaneous pedestrian volume. The spatial manoeuvres of individuals, their walking speed and trajectory on the pavement are related to overall flow density. Following Vansemu et al. (2017), we consider the distributions in bi-directional flow under conditions of high pedestrian flow and limited channel dimensions.

Let us review what we already know about impacts on pedestrian speed in the real environment.

In high-density pedestrian environments, the maintenance of pedestrian speed largely determines the throughput of the pedestrian facility. Walking speed varies by city and is generally higher as a function of average purchasing power and Gross Domestic Product per individual (Levine & Norenzayan, 1999). That study focussed on central business districts and certain times of day but did not account for varied situations within those same sampled cities. In a comparison of Indians and Germans tasked with walking in a confined channel, Chattaraj et al. (2009) found that they walked at the same speed, but Indians reserved less personal space. Within the broader consensus concerning variations across cities, pedestrian speed varies as a function of trip purpose, time constraints, the number of individuals in the cohort and a variety of personal characteristics. The frequency distribution of walking speed follows a normalized curve, whether in conditions of crowding or free flow (Corbetta et al., 2017). Walking speed is also influenced by the sound environment (Franek et al., 2019). Pedestrian crowding results in both aversive and attractive responses (Engelniederhammer et al., 2019), although we do not know how these responses affect speed.

A number of studies have considered the effect of geometry on flows and walking speed. The geometry of the walking space has a major effect on flows, in particular when one considers merged flows (Bustedde et al., 2001; Shahhoseini & Sarvi, 2019). When those flows become highly congested, the pedestrian trajectory may take a different form than in conditions of free flow (Shi et al., 2019). In multi-directional flows that occur often at street and indoor corridor intersections, individual trajectories may be altered in a major way in contrast with bi-directional flows (Cao et al., 2017). The effect of channel dimensions and effective channel width on speed is not well explored in the literature but would seem to hold promise given the variety of pedestrian strategies to move forward under conditions of crowding.

In the typical, outdoor urban environment pedestrian flows seldom reach those represented in the theoretical models, except in the event of mass public demonstrations. Most studies of pedestrian movement attempt to represent movement as flows, in recognition of the prevalence of group behaviour, particularly in dense pedestrian flows. Individual behaviours are seldom examined, although models have been proposed to include individual behaviour in a meso-scaled model (Tordeux et al., 2018), or to use laser detection of pedestrian position and trajectory in larger flows (Shi et al., 2019). Individual behaviours were studied in relation to a variety of group behaviours in a naturalistic study of the Galleria Emmanuele II in Milan (Bandini et al., 2014), using a cellular approach. Following these suggestions, the present study is intended to reveal the relationship between individual behaviours and group flows using empirical data.

In usual urban conditions, pedestrian speed observes a local norm and is consistent over time (Levine & Norenzayan, 1999). This result describes a condition where there are many persons behaving individually but are describable as aggregate flow models. Such movement appears quite different from the highly constrained situation of very dense flows, in excess of 5 persons/m^2, where all the obstacles to movement are other persons (Lian et al., 2017). In the everyday urban environment, physical obstacles and pathway configuration may have significant effect on travel speed. The extent to which these physical elements influence pedestrian progress in combination with pedestrian volume, needs further examination.

Many studies represent pedestrian movement as aggregated flows. It is widely recognized that under high density conditions, pedestrian traffic tends to channels. A channel might be identified by individuals acting as a cohort or might be more generally defined by left/right convention. For example, it is a widely recognized fact that pedestrians in the United Kingdom, Japan and Australia tend to walk to the left of the counterflow, while in North America and continental Europe, the opposite is generally observed. It has been found that rightward deviation is universal and due to rightward attentional bias but is influenced by car-driving practice (Thomas et al., 2017). The leftward directional bias in Tokyo and London has been anecdotally observed to be reduced by the large presence of non-native others. Hong Kong also has a left-driving practice. Adherence to convention should increase potential flow by reducing the rate of directional conflict. Counterflow and idiosyncratic behaviour has been examined in such circumstances to measure resulting decreased flow (Akpulat & Ekinci, 2019). It was also found that flows and counter-flows in adjacent channels, with or without crossflow, had no effect on the FD (Zhang et al., 2012), at least for the densities practiced in experimental studies. Although in space managed by the public transit corporation and in some buildings, directional signs are an attempt to channel pedestrians, but the question remains how these directives in private space are transferred to the public environment. Counterflows or individuals walking against the prevailing movement may reflect the ability of individuals to adjust body position or overtake others in their movement (Chen et al., 2018), as suggested in the seminal social force model (Helbing & Molnár, 1995).

Although it may be possible to find overall differences in walking speed among cities, it is also highly likely that there are differences among environments within the same city. The transport hub has been examined as a special case, in part because of the sudden generation of pedestrians into a spatially limited channel (Gu et al., 2019). In such constrained circumstances, it is often suggested that pedestrians would prefer to exit to the street environment where they are freer to define their paths. What are the speed differences in such indoor environments compared with the typical street pavements? What are the probable reasons for these differences?

Natural trajectories without obstacles are not Euclidean (Ruggiero et al., 2018) and can be described by a polynomial function (Bustedde et al., 2001). The more obstacles that lie in the path defined by a heading, the more deviation. Although it is broadly assumed that such deviation must have a negative effect on travel speed, this is not yet revealed in empirical work (Cao et al., 2017); hence our attempt to reveal to what extent under conditions of moderate crowding, deviation may reduce speed. Alternatively, deviation from a straight trajectory may be a strategy for maintaining speed, although this remains to be confirmed.

Aside from detecting an available channel opposite the dominant flow, there are other manoeuvres available to maintain or enhance speed. It is suggested that body rotation allows the pedestrian to pass by individuals when the space would normally be insufficient to pass with the body facing the flow direction. Theoretical body movement is borne out with experimental work (Yamamoto et al., 2019). Deviation from an observed heading can also serve the purpose of overtaking a group of individuals or to avoid collision when the oncoming pedestrian would otherwise run into the target individual. Pedestrians compute, more or less, the multiple trajectories on a limited channel to determine the optimal path, which inevitably involves deviation when speed is at or greater than the average. A flexible centreline in bi-directional flows results from cohorts of various sizes passing each other, as confirmed by observation inside a shopping centre (Zhang et al., 2019). Compression of the cohort to execute this manoeuvre will be followed by pedestrians dispersing

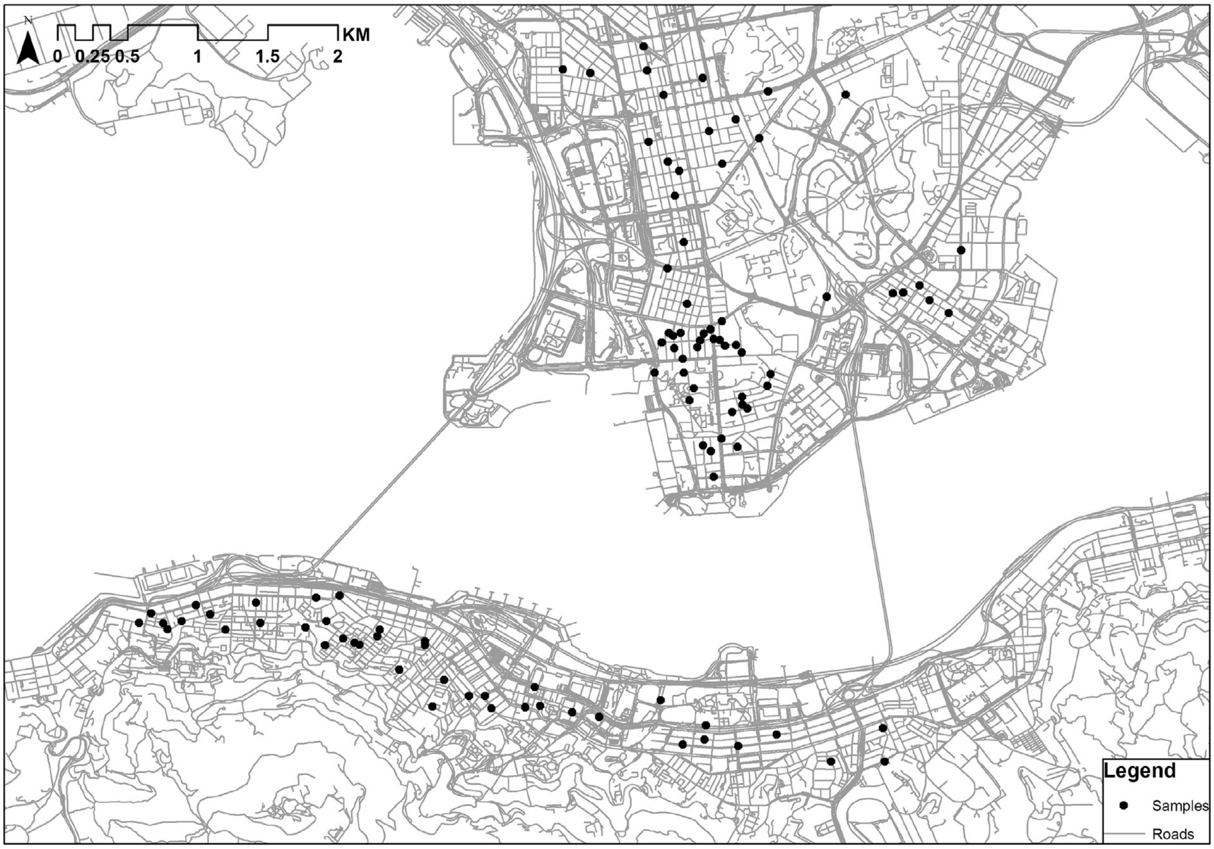

Fig. 1. The locations for field study of the pedestrian environment.

Fig. 2. Three frames from lateral views of the study frame and three frames from the direct view.

within the given channel (Zacharias, 1999). These behaviours are very complex in nature, but it remains to be seen whether they overcome the several friction factors to reach desired walking speed, a purpose of the present work.

We focus on the public environment of a particularly high-density environment to extract the effects of the following environmental attributes of the pavement on walking speed: the total width of the pavement, the effective width, pedestrian volume, pedestrian flow rate and deviation. The particular examined strategies of pedestrians to maintain speed are the following: deviation and adherence to right- and lefthandedness. A sample of 24 locations is an attempt to represent a wide variety of walking conditions in the public environment and to capture behaviours generalizable across environments in the same city. These outdoor locations are compared with the walking speeds at 7 underground corridor locations associated with mass transit (MTR) to estimate a speed baseline for Hong Kong and in conditions without shopping.

2. Methods

The fundamental diagram is derived for pavements. Speed and lateral displacement in the trajectory are related to width, effective width, sex and pedestrian density. Lane formation is examined. Speed is compared with that in indoor corridors of the Mass Transit Rail (MTR) system.

Pavements with commercial frontages (n = 24) were selected in central Hong Kong to represent a wide range of pedestrian volumes and pavement widths (Fig. 1), excluding locations with major entrances to shopping centres and office buildings. Pavement segments of 15 m in length were simultaneously videotaped in direct and lateral views in 5-min clips at various times over the course of three weekdays in late October (Fig. 2). Autonomous individuals were selected from the video clips using a randomizing protocol, excluding those using mobility aids, managing delivery trolleys or entering a shop within the study frame.

Selected individuals were plotted in plan as a function of time over the pavement segment (Fig. 3). Travel time is measured from the start of the segment when part of the body enters the measurement frame to when all of the body exits the frame. Speed is measured using the linear measure of travel distance, not the distance associated with the travel trajectory. Deviation is normally measured in relation to a heading; however, such measurement is operationally difficult because individuals are frequently changing heading at the micro-scale. We measure the amount of lateral displacement they make over the segment, recording the minimum and maximum displacement from the outer edge of the pavement. In this way, an individualized measure is derived of lateral displacement in relation to speed and pedestrian density.

Specific bi-directional pedestrian volume was measured at a cordon bisecting the study frame and for an interval of 60s with individual travel time, 11s on average, within the interval. Specific volume reduces the transient effects of volume fluctuation, while averaged volumes might be at different levels. Peak volumes are higher than those recorded in many cases but were difficult to analyze using our field methods.

Obstacles were plotted to derive effective width over the study frame. Planter boxes suspended from the fences, trash receptacles, parked trolleys and other equipment usually at the fence as well as displays on the pavement in front of the shop are typical examples, 16% of the pavement width over the entire sample. The survey was conducted before the street demonstrations starting in 2019, when the fences were still installed on the street, along with the planter boxes.

Directional channelling was measured by *post hoc* examination of the videos. This analysis examines the role of counterflow, that is opposite to conventional or dominant flow. Since channelling offers efficiencies in flow, in what circumstances do counterflows occur? A lateral cordon is selected in a free-flow section of the pavement with a centreline in the longitudinal sense (Fig. 4). Walking direction of all pedestrians is recorded as well as the channel at the cordon. The relationship between non-observance of prevailing movement

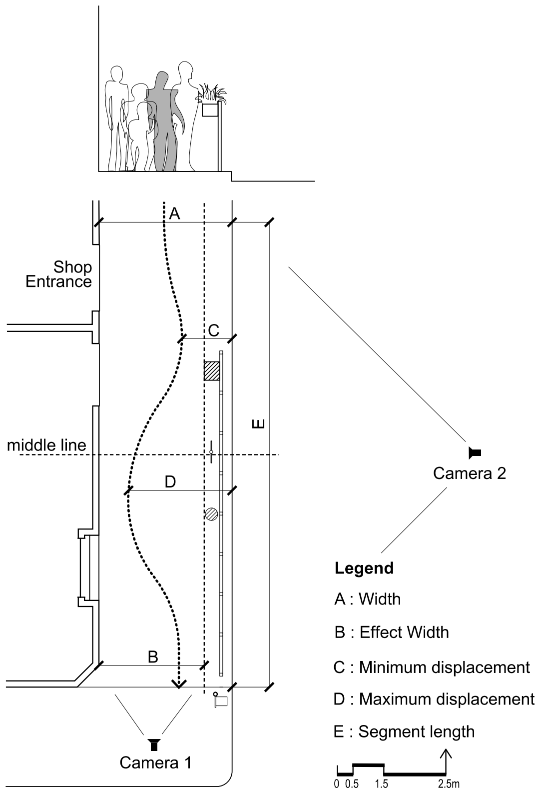

Fig. 3. Measurements from the video survey.

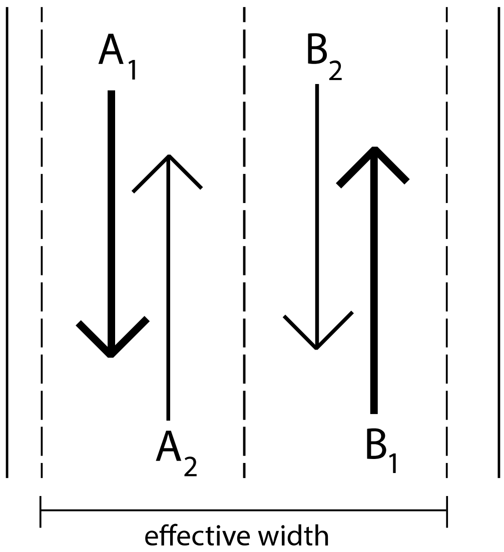

Fig. 4. Direction and channel measurement.

direction per channel and overall volume, directional bias, left-right movement ratio, and dominant flow volume are examined with correlational analysis.

Baseline walking speed was measured for comparison with the street condition. Walk speed measurement was conducted at 7 underground locations, on the new, long corridors associated with the westernmost stations on the Island Line on Hong Kong Island. The corridor tunnels are without shops, taking MTR users from the street to the station. Some of the corridors are at a slight slope and all are air-conditioned. Individuals were randomly selected using the same randomizing protocol as for outdoor locations (n = 356).

3. Results

The descriptive statistics are provided in Table 1.

Flow versus density reveals the typical linear relationship through lower levels of density. A quadratic function best fits the data in regression (Fig. 5), confirming the theorized distribution proposed by Hoogendoorn et al. (2018). The concave function for the pedestrian flow-density relationship is then only partially corrected by myriad manoeuvres of pedestrians attempting to maintain pace. The speed/density relationship is more dispersed than seen in the results of experimental studies, with density explaining up to 15% of variance in speed when other explanatory variables are excluded (Fig. 5; $R^2 = 0.144$; $F = 19.762$; $p = .000$).

A comparison of the walking speed frequencies for pavement and corridor conditions clearly shows that walking in the underground corridors is significantly faster than on the pavements (Fig. 6). Both follow the same distribution over velocity ranges. There is little to distinguish the populations, except for possibly a larger proportion of elderly on the pavements. Their presence has no detectable effect on mean walking speed, however, because of the distribution and the relatively small number of slow-moving individuals.

Lateral displacement is significantly and negatively related to walking speed, as might be expected, although the impact on walking speed is small, at 4.7% variance. Lateral displacement results from overtaking or collision avoidance and effectively lengthens the traversed distance for the given segment. Minimum displacement from the pavement edge is positively associated with walking speed, while maximum displacement is negatively related. Maintaining position at the outer edge of the flow is associated with slightly higher speed, while walking near the façades is associated with slower speeds overall, the two variables accounting for 6.6% variance. It should be noted that as displacement increases, so does the real length of the trajectory, while measured speed is Euclidean.

Next is the question of what physical features might account for these differences in speed over the plan of the pavement segment. The results of the regression model are summarized in Table 2. In theory, more shops may result in more interaction between the

Table 1
Pavement attributes and sample pedestrian trajectories.

	Mean	SD	Minimum	Maximum
Males (n = 107; m/s)	1.21	.21	.66	1.74
Females (n = 109; m/s)	1.10	.20	.57	1.58
Effective width (m)	2.57	.88	0.80	6.80
Width	3.04	1.01	1.00	7.00
Pedestrian volume (P/m)	32.51	23.42	3.00	78.00
Pedestrian flow (P/m/s)	10.60	6.61	1.50	25.71
Displacement	0.53	.45	0.00	3.30

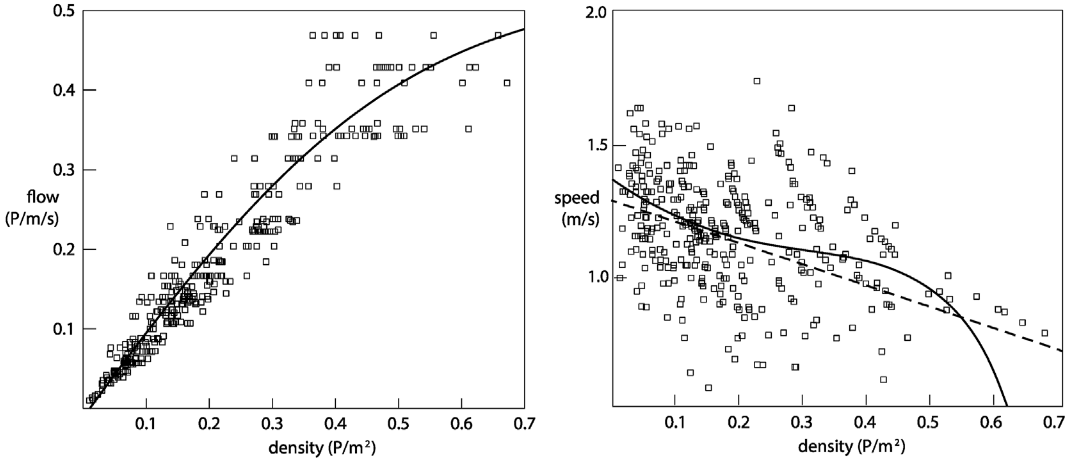

Fig. 5. Flow/density relationship for 24 pavements in Hong Kong with quadratic fitted line (left); speed/density relationship with cubic and linear fitted lines (right).

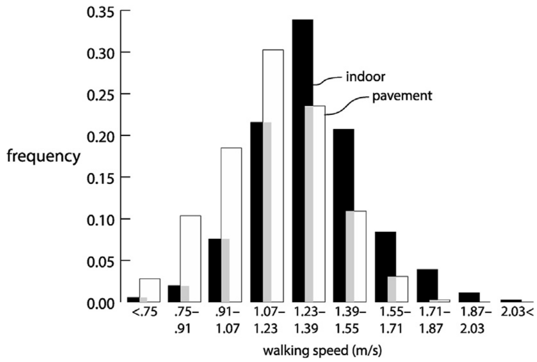

Fig. 6. Walking speed distributions on pavements and in MTR corridors.

Table 2
Regression model (quadratic) for walking speed.

		R^2	F-value
		137	9.219**
Regression Variable	Regression Coefficient	SEE	Standardized B
Sex	.089**	.021	.209
Shops	-.018*	.008	-.111
Effective Width	.054**	.019	.141
Pedestrian Volume	.000	.000	-.019
Displacement	-.078**	.022	-.182
Width	-.029	.016	-.188

*p < .05; **p < .01.

pavement flows and shop flows, potentially reducing speeds. As expected, the density of shops is slightly and negatively associated with speed, accounting for 2% of variance. Shop density varied only from 0 to 7 on the 24 segments, so it is likely the effect could be much larger in conditions where shop density was much higher, or where shopping activity was more intense.

Obstacles to linear movement on the pavement are also negatively and significantly related to speed, independently of the width of the pavement or the effective width. The effect is not large at 1.6% of variance, but perhaps commensurate with the proportion of the walking surface occupied by these features. Effective width is slightly and positively associated with speed, also at 1.6% of variance.

All of the above results suggest that the physical conditions of the pavement have a significant impact on walking speed. We now consider the case that pedestrian flow density might be dependent on these same independent variables, this time including speed. Indeed, pedestrian flow density is positively related to speed and accounts for 3.8% of variance, although it is difficult to determine what is affecting what. On the other hand, lateral displacement is not significant, nor are obstacles.

Now we enter all the variables in a multiple regression with speed as the dependent in order to take account of the pedestrian flow as an additional major factor in walking speed (Table 2). Width is removed since it is highly correlated with effective width.

The results of the bivariate analysis hold up in the multiple regression; that is, shops, displacement, and obstacles are all negatively associated with walking speed, while effective width has a positive relation. Pedestrian flow is unrelated to walking speed, perhaps the most important result. Overall, the model explains 13.7% of variance in walking speed.

3.1. Channelling and counterflows

The intent of the following analysis is to examine response to spatial interaction between and among moving pedestrians. The subset of videos is examined for channelling and counterflows (n = 54), after removing those with very low pedestrian volume, those without a consistently dimensioned pavement and with less than 3 m effective width. Every individual is tracked across a cordon, while nearest neighbours are ignored.

There is a clear righthand bias to movement at all pavement widths and volumes, in keeping with the suggestion of Levine and Norenzayan (1999). Nevertheless, counterflows to the dominant flow for each side of the pavement make up .41 of the total flow. There is no relationship between the counterflow rate and total pedestrian volume, contrary to expectations. There is also no significant relationship between counterflow rate and the A/B proportion, also contrary to expectation. Counterflow is reduced substantially as dominant flow within channels increases, however (A: −.402, $p < .01$; B: −0.467, $p < .01$). This makes sense to the extent that the channel is already saturated with unidirectional movement.

As noted above, higher speeds are often associated with a trajectory on the outer edge of the pavement, which may be opposite to the conventional flow. Nearly half of the cases of counterflow (A_2, B_2) are temporary but repeated. The remainder are cases remaining within the channel and often part of a cohort.

3.2. Displacement

The minimum and maximum displacements from the outer edge of the pavement were measured for each target individual in the study frame. The difference between the two represents the amount of deviation from a straight heading. We hypothesized that as the amount of deviation increases, speed would decrease. There are two possible explanations: firstly, the total trajectory is longer with greater deviation than if heading were maintained and secondly, individuals are avoiding collision. If speed were to be positively associated with deviation, then such manoeuvres are for the purpose of maintaining higher speed than that of the cohort. As expected, there is a significant decline in speed as a function of deviation (Fig. 7; $R^2 = 0.048$; $F = 17.726$; $p = .000$). Maximum displacement refers to the maximum distance from the outer edge, or in general, the tendency to approach the building. Diminished speed might be expected where there is more shopping and more interaction with movement emanating from buildings. Such decline in speed is also observed (Fig. 7; $R^2 = 0.044$; $F = 16.101$; $p = .000$). The outer edge of the pavement sees slightly faster movement. Elderly individuals using mobility devices generally adhered to the centreline of the pavement, as did those operating pushcarts, generally allowing pedestrian flows on both sides. Gorrini et al. (2016) also found that the elderly maintained heading in their study environment.

4. Discussion

The FD generated by these field data bears resemblance to those already derived from theoretical models and laboratory experiments; for example, Hoogendoorn at al. (2018). Although these are among the densest pedestrian urban environments worldwide, there remains a strong linear relationship between pedestrian flow and pedestrian density, with the slight attenuation at the highest flow levels. The stability of this relationship over a substantial range of values evokes the ability of pedestrians to engage in several different manoeuvres that assist in maintaining travel speed. The effects of variable distribution by direction has no effect on observed aggregate speed, a finding similar to that of Cao et al. (2017) and Zhang et al. (2012) in their studies of bi-directional and multi-directional flows. In the second of these studies, rate of conflict in opposing streams of movement had no effect on the FD. Although the densities in these experimental studies are high when compared with typical, outdoor walking environments in cities, they are not sufficiently high to have significant impact on flow.

Travel speed is generally higher in the dedicated access corridors of the MTR, where there is almost always free flow, no crossflows and where pedestrians tend to move in channels. The highest walking speeds in the underground (Fig. 6) are not represented in the pavement studies, because it is extremely difficult to achieve those higher speeds when speeds tend to be clustered around a much lower mean value and where pedestrian density is already relatively high. In the underground, there are directional markings on the pavement and on the walls, with occasional verbal reminders of the suggested channels for walking. It is not clear that these directives are observed, however, or have any impact on walking speed. The reasons for the higher walking speed remain unexplored here. The many visual distractions of the street environment might be a reason for a general slowing of pedestrian traffic even if desired walking speed is still attained; the underground MTR corridors have blank, smooth walls and uniform floor finishes.

We can see that pedestrian speed is sensitive to several local, environmental variables although the effects are not large. Pedestrian walking speed varies considerably over this sample, which helps explain the relatively small contribution of each of the physical variables. Pedestrians maintain speed by deviation from a straight line, overtaking slower individuals and trolleys; however, this pedestrian speed has no relationship with the overall pedestrian flow, or the density of pedestrians on the pavement.

The results from 24 sites across the city tend to a coherent result with regard to the variables we have investigated. The maintenance of pedestrian flow suggests considerable adaptation on the part of pedestrians to conditions experienced every day. Whether this is

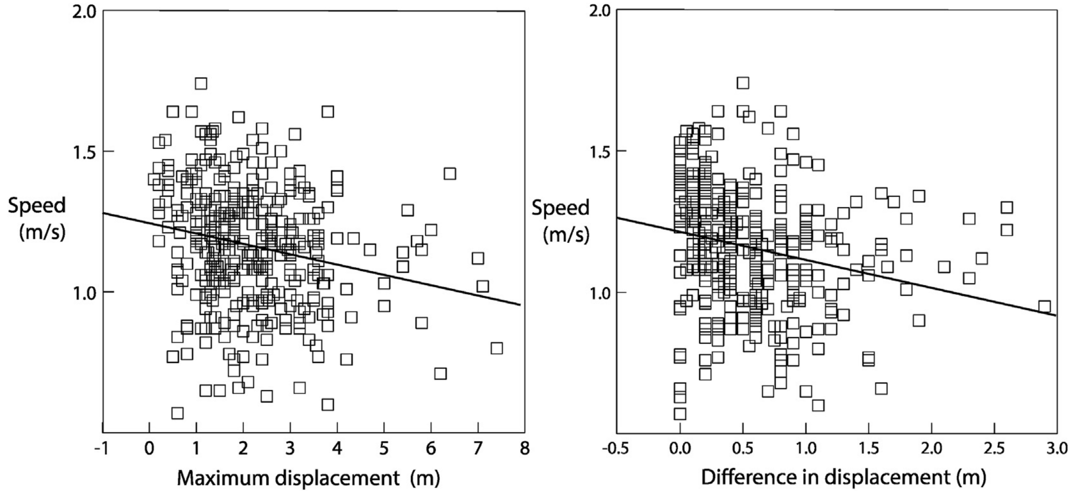

Fig. 7. Speed as a function of maximum displacement from the outer edge of the pavement (left), and total lateral displacement (right).

simply adaptation to the physical constraints of walking in such a high-density environment, and whether there are underlying cultural factors in this outcome, cannot be known from this study, although uncovered in experimental studies (Chattaraj et al., 2009). It would be useful to compare this case with similar ones in a different cultural context, where pedestrian flows are also very high.

The particular spatial behaviours observed on Hong Kong pavements also suggest that pedestrians have adapted to local conditions of a narrow space with substantial multi-directional flow. Slower individuals pass close to the shops where there are more obstacles and where individuals are entering and exiting. Faster individuals travel on the outer edge of the pavement, while the slowest individuals are almost invariably in the middle. These behaviours are consistent across the 24 sites, suggesting that local environmental factors are not inducing the behaviours directly. Rather, there is a generalized pattern of behaviour that may be in part a response to typical environmental conditions. That they behave somewhat differently collectively in the controlled environment of the MTR suggests they have a different reading of that environment and the appropriate behaviours. To investigate that possible relationship, it would be desirable to add other types of environments such as open and climate-controlled walkways and shopping centre concourses.

What does this study tell us about management of the street walking environment? The ability to adapt to the limited spatial conditions of the present case is evident and leads to particular, shared walking protocols. Nevertheless, walking speed would increase if effective pavement width were increased, while displacement manoeuvres and mixing in channels would decrease, undoubtedly improving pedestrian comfort.

5. Conclusion

The pavements of Hong Kong are relatively narrow. In a sample of 24 locations with varying pedestrian volume, pavement width varies from 1 to 7 m. Effective width recognizes the space of landscaping features associated with a fence or sales displays at storefronts. Maximum pedestrian volume is 78 persons per minute, or 4680 persons per hour. Although it was expected that under conditions of high pedestrian flow that pedestrians would channel by convention, 57% were righthanded when the pavement was virtually divided into two equal width channels. Counterflow was significantly reduced when the dominant flow was higher.

Pedestrian flow is positively related to pedestrian density through the range considered in our study. The distribution is best described by a quadratic function, suggesting a plateau for pedestrian flow and subsequent decline. In the context of the public environment of Hong Kong, however, these high levels of density and flow are a very small proportion of the streets in the busiest areas of Hong Kong Island and Kowloon.

Pedestrian volume and the width of the pavement have no significant effect on walking speed, although the effective width of the pavement has significant positive effect. Lateral displacement to overtake or avoid oncoming pedestrians was positively related to speed, while the presence of shops was negatively related to speed. Overall, 13.7% of variance in walking speed is explained by the 6 variables of our model, including the sex of the observed individual. This estimate is likely conservative because there remain many uncontrolled local environmental variables in the present study.

Declaration of competing interest

I declare that I have no conflict of interest in the preparation of this manuscript. All data are mine, as is the analysis and the text of the manuscript.

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