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PHYSICAL SPACE DESIGN FACTORS AFFECTING PEDESTRIAN MOVEMENT ON THE PRECINCT SCALE IN SINGAPORE

JIANG YINGYING
Future Cities Laboratory, Singapore-ETH Centre, Dense and Green Building Typologies Project
jiang@arch.ethz.ch

LI HENGSHAN
Future Cities Laboratory, Singapore-ETH Centre, Cognition, Perception and Behaviour in Urban Environment Project
li@arch.ethz.ch

CHRISTOPH HOELSCHER
Future Cities Laboratory, Singapore-ETH Centre, Cognition, Perception and Behaviour in Urban Environment Project
choelsch@ethz.ch

SACHA MENZ
Future Cities Laboratory, Singapore-ETH Centre, Dense and Green Building Typologies Project
menz@arch.ethz.ch

THOMAS SCHROEPFER
Architecture and Sustainable Design, Singapore University of Technology and Design
thomas.schroepfer@sutd.edu.sg

ABSTRACT

This paper investigates design factors that can influence pedestrian movement on the precinct (around eight to ten building blocks within a land plot) scale in Singapore through a comparison between Space Syntax analysis and actual pedestrian movement flows. The hypothesis of this paper is that pedestrian movement is influenced not only by spatial intelligibility as analysed by space syntax but also by numerous physical environmental factors. The main research question addressed in this paper is what environmental factors impact pedestrian movement on the precinct scale. The paper describes research on two recently completed residential developments in Singapore that are of similar scale and residential densities: The Interlace, a private development, and Punggol Waterway Terraces I, a public housing project.

The paper assesses outdoor movement potential through space syntax analysis and actual pedestrian movement as recorded by field observation in these two locations. Differences between the potentials and actual pedestrian movements are presented through comparison. The paper then presents interviews and social surveys that were used to investigate residents' space perception and space preferences for different activities. Combining this with the physical space quality analysis, the paper then summarizes the factors influencing people's movement.

KEYWORDS

Singapore, space design, space syntax, pedestrian movement, precinct

1. INTRODUCTION

Pedestrian movements include a wide range of activities, such as travelling, personal recreation, and social activities, which vary in terms of frequency, duration, route, and effort, among other factors. Identifying and evaluating design factors that influence pedestrian movements and route choices are important to prioritise measures and allocate resources to design comfortable, functional, and pedestrian-friendly residential quarters. Space patterns such as urban configurations are a key generator of aggregated patterns of pedestrian movement in urban scale; this phenomenon has been outlined as a generic process, and developed a methodology of space syntax for spatial description and analysis (Hillier, 1996; Hillier & Hanson, 1984; Hillier, Penn, Hanson, Grajewski & Xu, 1993; Penn, Hillier, Banister & Xu, 1998; Peponis, Ross & Rashid, 1997). A large body of research on space syntax has found that spatial configuration correlates with observed movement flow as well as individual wayfinding at both urban scales (Barros, De Silva & Holanda, 2007; Berhie & Haq, 2015; Choi & Koch, 2005; Dawson, 2003; Turner, 2007) and indoor environments (de Arruda Campos, Lemlij & Manning, 2007; Fujitani & Kishimoto, 2012; Heo, Choudhary, Bafna, Hendrich, & Chow, 2009; Hölscher & Brösamle, 2007; Hölscher, Brösamle, & Vrachliotis, 2012). Apart from the spatial configuration, functional properties of urban environments such as density and land uses have also been found to be correlated with pedestrian movements in urban areas (Choi, 2013; Ozer & Kubat, 2007).

Compared to large-scale urban areas, the association between pedestrian movement, space configuration, and physical space design factors has received little scholarly attention at the precinct scale. Precincts in Singapore usually refer to clusters of public housing blocks designed and built as a single area. Comprising averagely eight to ten building blocks, precincts are basic units in the development of Singapore: they group up into neighbourhoods; and around nine neighbourhoods consist of a new town. Pedestrian movement in precincts linking directly building blocks connect through to other means of transportations. They play significant roles in either the first and the last mile of public transportation journeys or footpaths for short-distance trips with a range of purposes. Different from urban networks, pedestrian networks on the precinct scale are always considered and designed as a part of outdoor recreation areas or the landscape. This landscape-oriented network design aims more to provide a pleasant physical environment rather than a nice walk experience, which weakens the considerations about the walkability of precinct-scale walkways as connections within or outside of precincts. Correspondingly, pedestrian movement at the precinct scale differs from that in urban areas and indoor environments. The pedestrian movement in a particular precinct is conducted typically by the people who are familiar with and have built cognitive maps of designated areas and the surrounding neighbourhoods. Instead of freely exploring the environment as strangers, precinct pedestrians are more likely to choose their paths based on their personal preferences such as sidewalk width, existing greenery, and so on. Pedestrians on the precinct scale may have a diversity of motivations. Residents may walk around the precinct for exercises or leisure activities rather than travelling to a particular destination, which weakens the influence of path distance on pedestrian movement. Therefore, precinct-scaled pedestrian movements and route choices tend to be less correlated with space configuration than in urban areas and indoor environments.

Based on the hypothesis that precinct-scaled pedestrian movements are influenced more by physical spatial design factors than spatial configuration, this study intends to answer the question of which physical space design factor(s) effect pedestrian movement and route choices if the spatial configuration does not solely affect pedestrian flows. The study compares observed pedestrian path choices with connectivity and integration analysis of space syntax in two residential precincts in Singapore with the purpose of examining this hypothesis. An on-site interview and survey ensued to collect residents' route choice preferences as well as their underlying considerations of spatial factors for choosing routes. These included path width, traffics, and greenery around the walkways.

As a "City-in-a-Garden", Singapore has been developing pedestrian networks from the urban to the precinct scale as an important part of the urban blueprint. Relevant research on walkability has been attracting more and more attention from the Government of Singapore due to its benefits related to public health and sustainability. Creating more pedestrian-friendly neighbourhoods and an enjoyable walking experience has been considered an important basis for sustainable transportation.

The primary goal of this paper is to answer the question which physical space design factor(s) may influence pedestrian movements and route choices if the spatial configuration does not (or not solely) affect pedestrian flows at the precinct scale in Singapore. The study compares the observed pedestrian path choices with connectivity and integration analysis of the space syntax method in two residential precincts in Singapore. This was followed up with on-site interviews and surveys for collecting residents' route choice preferences as well as their underlying considerations of physical space physical factors for choosing routes.

2. DATASETS AND METHODS

To investigate actual pedestrian movements in precincts, two residential developments in Singapore were selected. They are Punggol Waterway Terraces I, a public housing precinct, and The Interlace, a private condominium precinct (Figure 1).

Figure 1 - Locations of the two selected residential precincts in Singapore

Figure 2 - Overviews of Punggol Waterway Terraces I

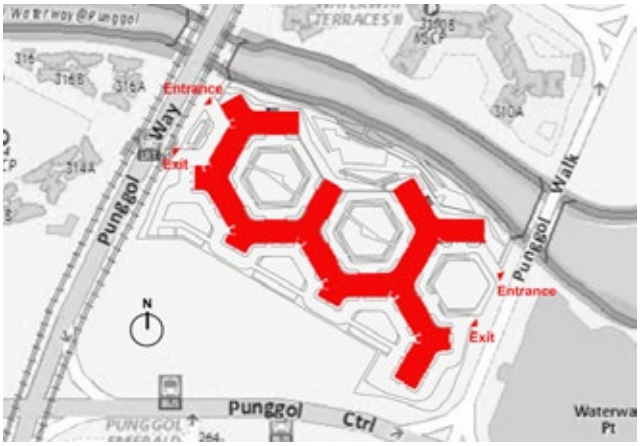

Figure 3 - Location of Punggol Waterway Terraces I, including residential building block (red part) and two main entrances on Punggol Walk and Punggol Way.

Completed in 2015, Punggol Waterway Terraces I (Figure 2) is located in the recently developed Punggol New Town in the northern part of Singapore. The precinct consists of an 18-storey residential building, a car-parking basement, and an eco-deck surrounding two hexagonal courtyards with tropical greenery. It is located adjacent to the Punggol Waterfront Walkway and connected to it through a garden on the ground floor in the north. Facilities surrounding the precinct include a shopping centre and Massive Rapid Transit (MRT) terminal station on the other side of Punggol Walk, and a Light Rapid Transit (LRT) station on Punggol Way.

The Interlace (Figure 4) is located adjacent to the downtown area on the east coast of Singapore. Designed by OMA / Buro Ole Scheeren / RSP and completed in 2013, this precinct is one of the largest and the most ambitious residential developments in Singapore. Typologically, this precinct introduces a stacked system of 6-storey blocks around eight hexagonal courtyards with various programmatic themes. The precinct is located next to two national parks and is isolated by an urban expressway and two main streets. A shuttle bus service is provided to connect the precinct with nearby neighbourhoods and a shopping centre in the Harbourfront area.

Figure 4 - Overview of The Interlace

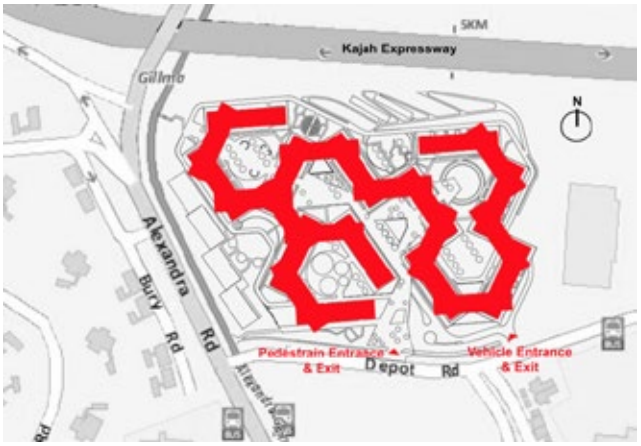

Figure 5 - Location of The Interlace, including residential blocks (red part) and main entrances for vehicles and pedestrian on the Depot Road.

Some similarities between these two precincts can be found: they were both completed within the last five years; they both consist of around 1,000 units; they both use hexagons in plan to organise the building blocks and courtyards; they both feature car parking in the basement to avoid interrupting outdoor activities from vehicle transportation; and they are both surrounded by major roads while being connected to nearby national parks.

Meanwhile, there are also considerable differences between the properties. As the site area is smaller than that of The Interlace, Punggol Waterway Terraces I has greater population density and building density. These two precincts also differ in terms of their household backgrounds. According to the policies in Singapore, public housing provided by the government is only offered to Singaporean citizens and permanent residents who have intermediate incomes. The Interlace features private properties and accommodates foreigners and households with high incomes. Furthermore, the facility provision in these two precincts also follows different standards. In addition to the playground and fitness equipment in both precincts, The Interlace provides a number of utilities to its residents, including swimming pools, barbeque pits, tennis courts, multi-purpose playground, etc.

Although the outdoor spaces in these two precincts are located on several levels (basement level, ground level, and podium level), there is no overlapping of outdoor spaces. By adding or revising accesses or connections, the spatial layout was transformed from three to two dimensions for the analysis in Depth Map.

The outdoor spatial layouts of these two precincts were firstly broken into the fewest and longest lines of sight that pass through all possible routes of movement in the axial map (Figure 7) through Space Syntax Depth Map (Turner, 2004). Some parameters were used for measurements, including:

- Connectivity: measuring the accessibility of each axial line to neighbouring axial lines by simply counting the number of connections per axial line;
- Integration: an important global variable measuring the relationship of each axial line to the whole urban system and the mean depth of each axial line in the network relative to all other lines (Hillier et al., 1993); and
- Intelligibility: the degree of correlation between connectivity and global integration values of the axial lines in spatial configuration analysis (Hillier, Burdett, Peponis, & Penn, 1987). It is hypothesised that high intelligibility ensures that the spatial configuration is predictable for pedestrian spatial distribution in urban areas (Hillier, 1999; Penn, 2001).

Apart from axial maps, segment maps were used in the current study, as segment maps divide each axis line at every connection point, making segment maps more feasible to study pedestrian

movement and transport than axial maps do (Turner, 2004). Lee & Seo (2013) examined built environment factors that affect pedestrian flow using space syntax and GIS-based methods. They found that the angular segment model provides a better explanation for the correlation than the traditional axial models. Thus, in this study we analysed these two precincts secondly by angular segment analysis (Figure 8). The parameter used for measurement was Segment Angular Integration, which measured how accessible each space was from all others within the radius by using the least angle measure of distance. This measure represents the movement potential of a street segment (Hillier et al., 2012).

We used non-participant on-site observation to measure the actual pedestrian flows in the two precincts. Thanks to the particular profiles of these two precincts and the shapes of building blocks providing with certain high spots above the ground, we were able to observe most of the sites without following or disturbing people. We observed most of the pedestrian movements and activities on the sites continuously and recorded the pedestrian trajectories in the public and green spaces out of building blocks. As both cases are residential precincts, pedestrians don't always start or finish their journeys at the edges of the precincts. The ends of the trajectories included the main entrances of the precincts, taxi drop-off/pick-up points, edges of the precincts, elevator lobbies and the doors of functional rooms.

We then counted the pedestrians based on the trajectory records. First, we divided the entire walkable areas of the precincts into spatial segments. Each segment was defined by two intersection nodes where people encounter some options in their paths (Figure 6). Within each spatial segment, people cannot change their directions other than walking forth and back. We counted people walking through the segments (from one intersection node to another one) in either direction. We didn't use the traditional gate count method here in this study as it could not reflect the pedestrian movements in square-liked areas with several paths heading in various directions. Pedestrian flows in these square-liked areas interwove together, which made it difficult to set up a single conceptual gate line to count pedestrians.

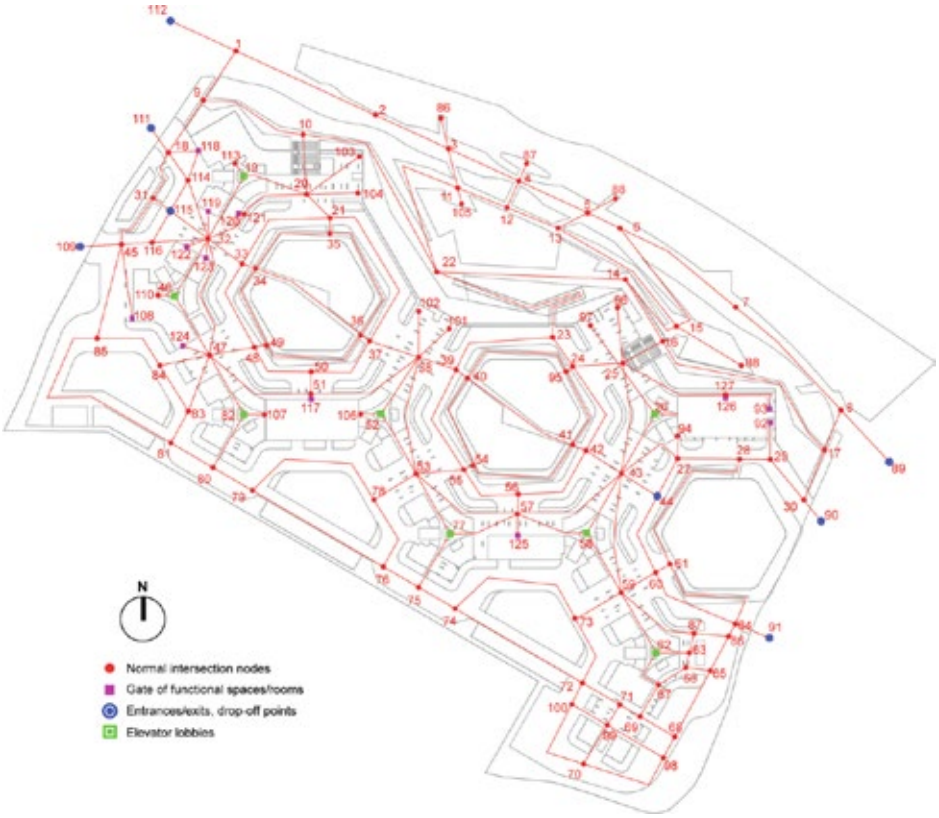

Figure 6 - Intersection nodes and spatial segments in Punggol Waterway Terraces I

Gehl (2011) classifies outdoor activities into three types—necessary activities, optional activities, and social activities—and states that space qualities influence optional activities more obviously than other activities. Therefore, this observation was conducted on both workdays and weekends over the span of two weeks, covering the hours between 8:30 am and 19:00 pm in order to concentrate on optional activities rather than necessary activities, such as travelling to school or workplaces during rush hours. Information of observed pedestrian movement, such as walking trajectories, were recorded. Over the course of the entire observation, more than 2,000 walking trips were observed and recorded in Punggol Waterway Terraces I and around 1,000 in The Interlace (Figure 9).

The study then focused on the paths showing the significant difference between space syntax analysis and actual pedestrian flows. Kevin Lynch's City Image theory (1960) was applied to display and categorise the environmental characteristics of those paths. The paths were divided into segments by intersection nodes. The correlations between space environmental features and actual pedestrian flow were established to understand what and how character categories can influence the number of pedestrians.

Lastly, semi-structured interviews and questionnaire surveys were conducted in order to understand the importance of each factor initially to the route choices by ranking the factors. Participants were selected randomly on site.

By combining the above information, the study addresses the implementation of space syntax analysis at the precinct scale, the environmental factors that can influence pedestrian movement, and the importance of these factors to pedestrians.

3. RESULTS

Figure 7 to Figure 9 show the axial map analysis, angular segment analysis produced by Depth Map, and actual pedestrian flow maps of these two precincts.

Through preliminary visual comparison between these analyses, it is clear that the actual pedestrian flows of The Interlace correspond to both axial map analysis and angular segment analysis well in terms of global integration and segment angular integration respectively. Differences between the axial map analysis and the actual pedestrian flows of Punggol Waterway Terraces I are evident; while the angular segment analysis matches, the actual pedestrian flows well in the central area of the precinct.

Table 1 shows the correlations between global integration and connectivity – intelligibility – in these two precincts calculated by Depth Map. High intelligibility of outdoor spaces in a precinct is likely to indicate a clearer hierarchic spatial structure, which is easier for human cognition based on the space configuration. In The Interlace this structure is apparent from entrances to the main street, to individual courtyards, and to residential blocks or facilities. It was expected that the differences existing in Punggol Waterway Terraces I might be due to the comparatively low intelligibility of the space. Surprisingly, both sites have relatively high intelligibility, and the one of Punggol Waterway Terraces I is even greater than The Interlace, which suggesting that pedestrian movements at the precinct scale cannot be predicted by spatial configuration solely.

Sites	Space syntax variable	Space syntax variable	Correlation (Intelligibility)
Punggol Waterway Terraces I	Global Integration (rad=n)	Connectivity	r = 0.806
The Interlace	Global Integration (rad=n)	Connectivity	r = 0.655

Table 1 - Correlations between integration and connectivity (intelligibility) of Punggol Waterway Terraces I and The Interlace by Depth Map

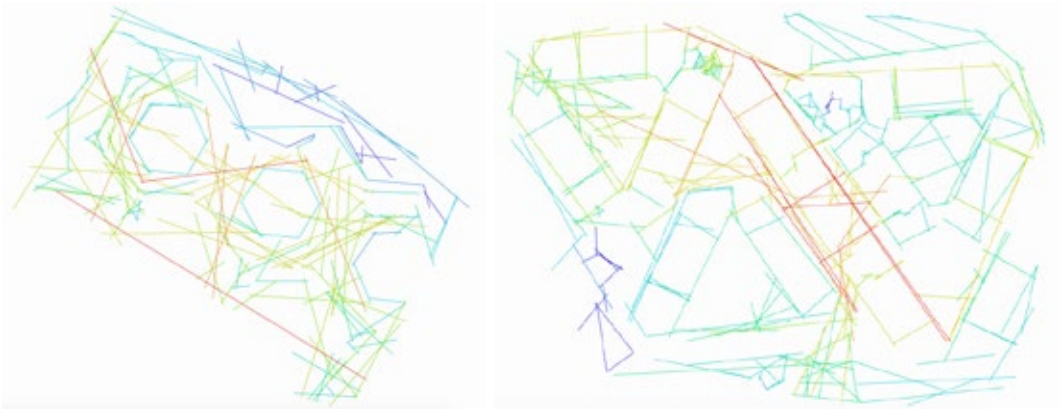

Figure 7 - Axial map analysis (global integration) of Punggol Waterway Terraces I (left) and The Interlace (right). The colour gradient from red to blue indicates the integration levels of axial lines from high to low.

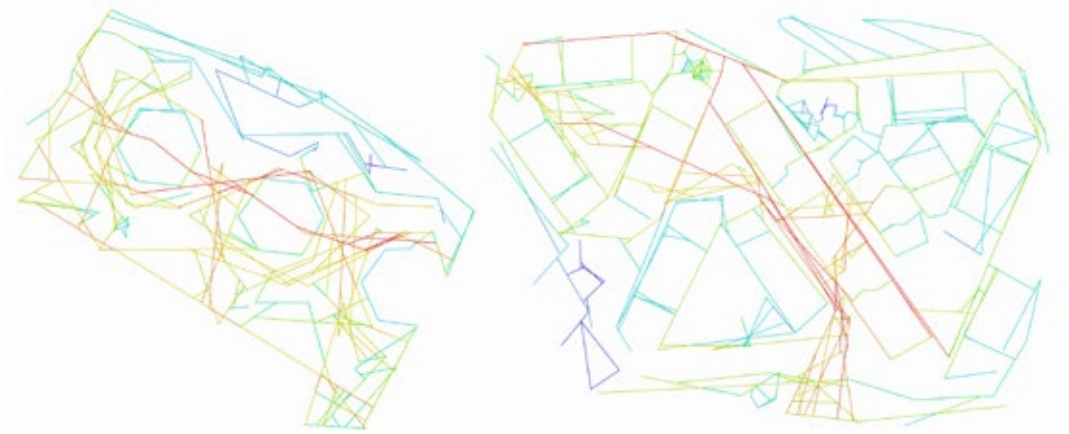

Figure 8 - Angular segment analysis of Punggol Waterway Terraces I (left) and The Interlace (right). The colour gradient from red to blue indicates the integration levels of axial lines from high to low.

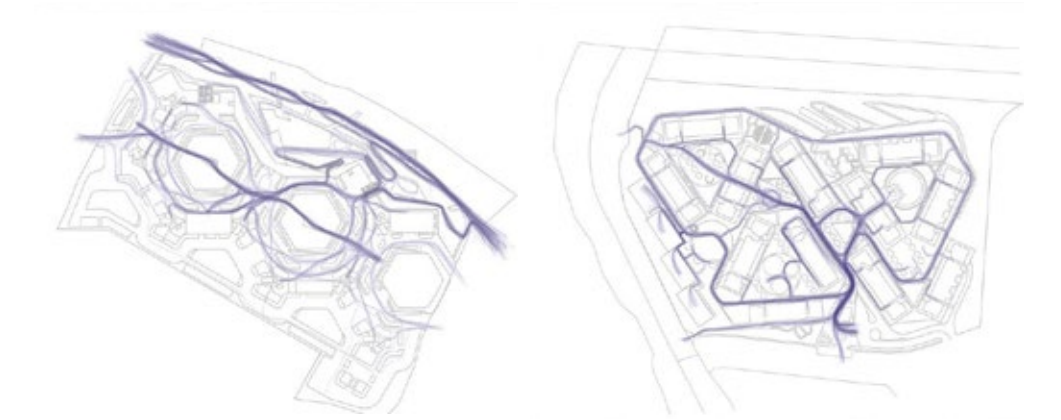

Figure 9 - Actual pedestrian flows by observation in Punggol Waterway Terraces I (left) and The Interlace (right)

Differing from the crisp and clear connectivity of street network or corridors because of clear boundary imposed by façade or walls at the urban scale, walkable (and inter-visible) areas at the precinct scale are usually designed as a part of open spaces, where pedestrians can move in arbitrary directions. As shown in Figure 7 and Figure 8, both the axial maps and the angular segment maps of the two precincts are not as clear as those in urban areas. Thus, it is very challenging, sometimes even impossible, to associate precinct-scaled pedestrian movement with a single axial line as opposed to a bunch of lines. In order to overcome this issue, GIS-based axial lines Figure 10 were used for axial map analysis in this paper, as shown in Figure 10. A Pearson correlation coefficient was computed to assess the relationship between integration and pedestrian flows. There was not significant correction between those two variables, r = -.080, n = 109, p = 0.408.

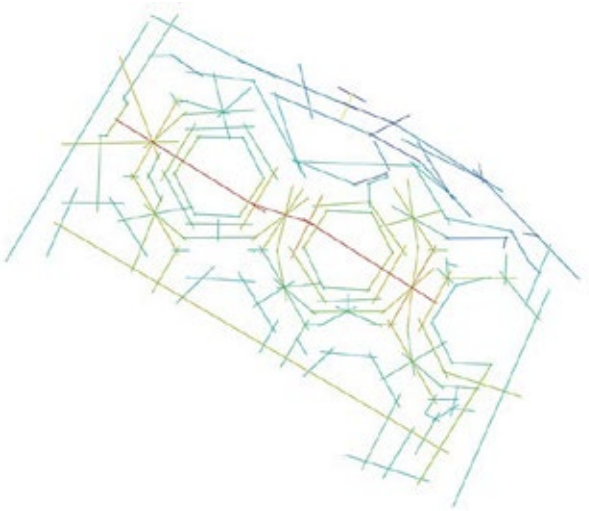

Figure 10 - GIS-based axial line analysis (global integration), navigation space in Punggol Waterway Terraces I. The colour gradient from red to blue indicates the integration levels of axial lines from high to low.

Figure 11 - Five selected paths in Punggol Waterway Terraces I

The precinct-scaled outdoor space of Punggol Waterway Terraces I is unique in that it connects directly to a national park, a neighbourhood shopping centre and transportation exchange terminal with abundant greenery. This to some extent increases the number of pedestrians in the northern part. To deal with this issue, we excluded data from this region (n = 5), and another Pearson correlation coefficient was computed to assess the relationship between integration and pedestrian flows. There was significant correction between those two variables, r =.360, n = 104, p < 0.001. This finding indicates that the urban infrastructure nearby largely impact pedestrian movements within a precinct, which shall be further investigated in future studies.

In order to investigate whether other physical space design factors can also influence pedestrian movements and route choices at the precinct scale in Singapore, we analysed the environmental characteristics of the Punggol Waterway Terraces I. Five paths were selected (Figure 11):

- Path 1 along the northern boundary, which was used most frequently in the precinct with average 38 pedestrians per hour;
- Path 2 crossing the precinct in the middle with around 11 pedestrians per hour;
- Path 3 connecting the inside residential blocks and the northern one with average five pedestrians per hour;
- Path 4 as a corridor crossing the precincts under the building structure with around four pedestrians per hour; and
- Path 5 along the southern part of the precinct which was seldom used during observation.

By analysing the space elements on these three paths based on Lynch's theory, the physical characteristics of these five paths are displayed in Table 2. Based on these features, each environmental factor was categorised and marked from 0 to 4 (Table 3). The segments composing those five paths were then classified into the categories under each factor. The distributions of these segments and their averages of the actual pedestrian flow passing through the segment per hour were presented in Figure 12.

The influences of each environmental factor can be generalised as follows:

- The most significant factors (Significance <0.001) for pedestrian flows are path surface materials, landmark nearby and mosquitos or harmful insects; and the significant factors (significance <0.05) are transport mode, path width, shade, path orientation and biodiversity.
- Pedestrians seldom appeared on the mixed path that was designated for both pedestrians and vehicles. People chose to use the paths only for walking or cycling.
- Paths with flat and soft surfaces, such as outdoor wood or decorative tiles were more popular than others.
- More pedestrians used the paths that were less than 4 meters wide.
- Pedestrians used the paths with small angular changes or without any angular change.
- Paths with clear landmarks nearby were used more frequently.
- Paths with good biodiversity, such as birds and butterflies, can attract more people to pass through. While the diversity of trees and other greenery was not a primary concern of the route choices.

	Path 1	Path 2	Path 3	Path 4	Path 5
					
Transport mode	Bicycles and pedestrian	Pedestrian	Bicycles and pedestrian	Pedestrian	Vehicle, bicycle and pedestrian
Elevation	No	No	Slopes	No	No
Path width	Around 4 meters	Around 2 meters	Around 8 meters	Around 2-4 meters	Around 5-9 meters
Cover	No	No	Partly	Completely covered	No
Shade	By trees	No	By buildings	By buildings	By buildings
Functional facilities	Fitness corner, playground	Playground	No	Pre-schools	No
Path edge	Vegetation	Fences and vegetation	Building structure	Building structure	Fences
Surface material	Concrete, colourful	Outdoor timbers	Concrete, colourful	Concrete, colourful	Concrete
Orientation	Direct to shopping centre and MRT station	Linking two main pedestrian entrances	Not clear	Not clear	Connecting main vehicle entrances
Surroundings	Many types of vegetation	Many types of vegetation	Building structure and one type of greenery	No	Building structure and one type of greenery
Landmark	MRT and shopping centre	No	No	No	No
Brightness	Natural and artificial lighting	Natural lighting	Natural lighting	Artificial lighting	Natural and artificial lighting
Biodiversity	Birds, butterflies, mosquitos, etc.	Birds and butterflies	No	No	No

Table 2 - Physical characteristics of the five paths in Punggol Waterway Terraces I

No.	Environmental factors	Parameters	Category
1	Transport mode	Pedestrians only	3
		Pedestrians and cyclists	2
		Pedestrians, cyclists and vehicles	1
2	Elevation means	No elevation	3
		By slopes or barrier-free facilities	2
		By steps	1
3	Path width	Narrow: less than 2 meters	3
		Medium: around 2 to 4 meters	2
		Wide: more than 4 meters	1
4	Covers	Covered completely	3
		Covered partly	2
		No cover or shelter	1
5	Shade	With shade of buildings and trees	4
		With shade of buildings only	3
		With shade of trees only	2
		Without any shade	1
6	Functional facilities	Connected to functional facilities	2
		Not connected to functional facilities	1
7	Path edge	Shaped by building structure	4
		Shaped by fences	3
		Shaped by vegetation	2
		Obscured edges	1
8	Path surface materials	Outdoor wood	4
		Outdoor tiles	3
		Decorated concrete	2
		Regular concrete	1
9	Path orientation	Straight forward	3
		Turning with small angles	2
		Turning with large angles	1
10	Landmark	With visible landmarks	2
		Without visible landmarks	1
11	Brightness	Natural light and artificial light	3
		Artificial light only	2
		Natural light only	1
12	Diversity of vegetation	With a variety of vegetation	2
		With single type of vegetation	2
		No vegetation	1
13	Biodiversity	With a diversity of birds or butterflies	2
		Without any birds and butterflies	1
14	Mosquitos or harmful insects	Without mosquitos and harmful insects	2
		With mosquitos and harmful insects	1

Table 3 - Categorization of environmental factors

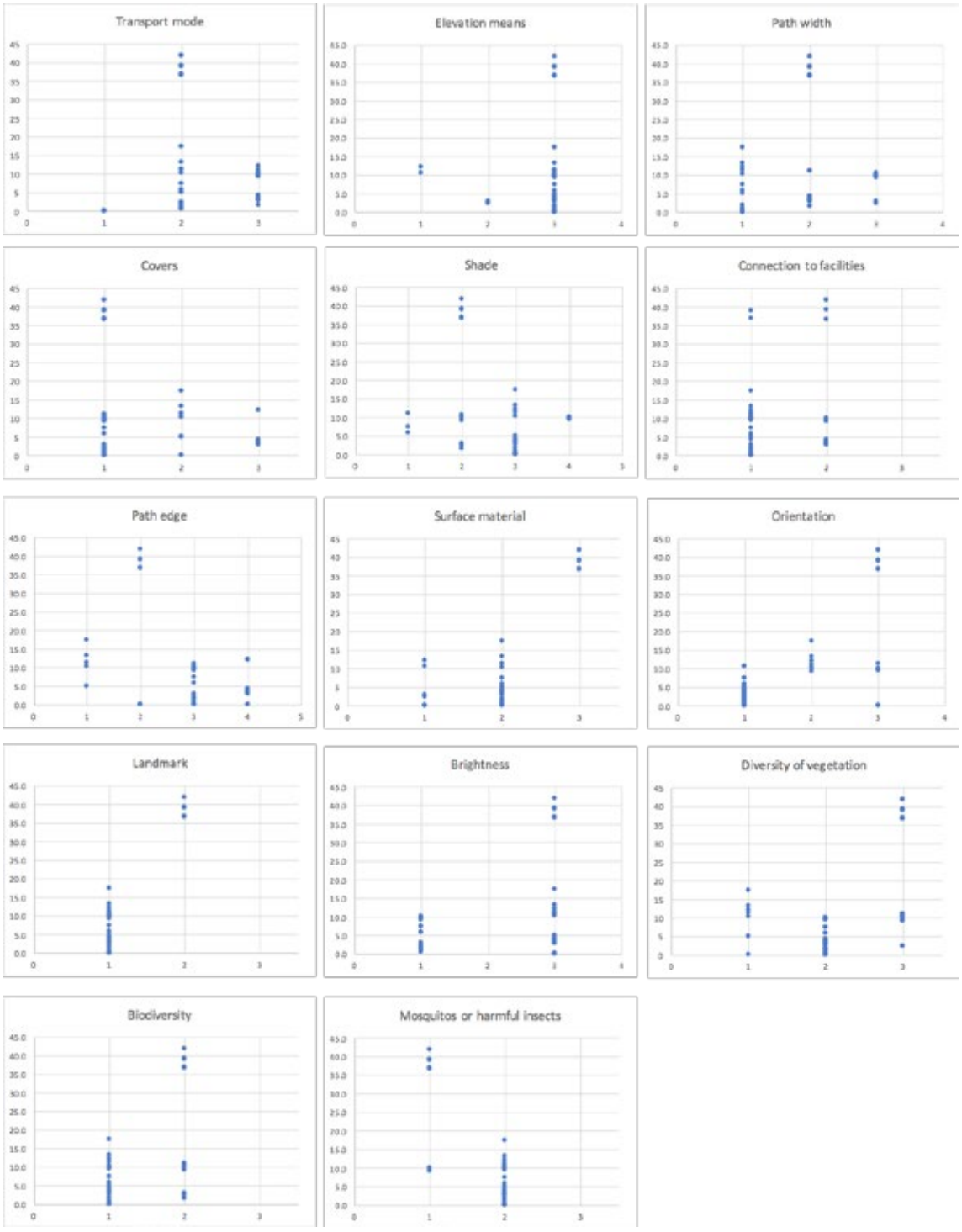

Figure 12 - Distribution of actual pedestrian flow per hour in order of categories of each environmental factors

No.	Environmental factors	Parameters	Significance
1	Transport mode	0.472**	<0.01
2	Elevation means	-0.095	0.543
3	Path width	0.406**	<0.01
4	Covers	0.121	0.439
5	Shade	-0.305*	<0.05
6	Functional facilities	0.241	0.119
7	Path edge	-0.234	0.130
8	Path surface materials	0.583**	<0.001
9	Path orientation	0.325*	<0.05
10	Landmark	0.559**	<0.001
11	Brightness	0.024	0.878
12	Diversity of vegetation	0.235	0.130
13	Biodiversity	0.458**	<0.01
14	Mosquitos or harmful insects	-0.547**	<0.001

**: Correlation is significant at the 0.01 level. *: Correlation is significant at the 0.05 level.

Table 4 - Spearman rank-order correlation coefficient between pedestrian flows and physical environmental factors

Result of ranking on the importance of environmental factors to pedestrians

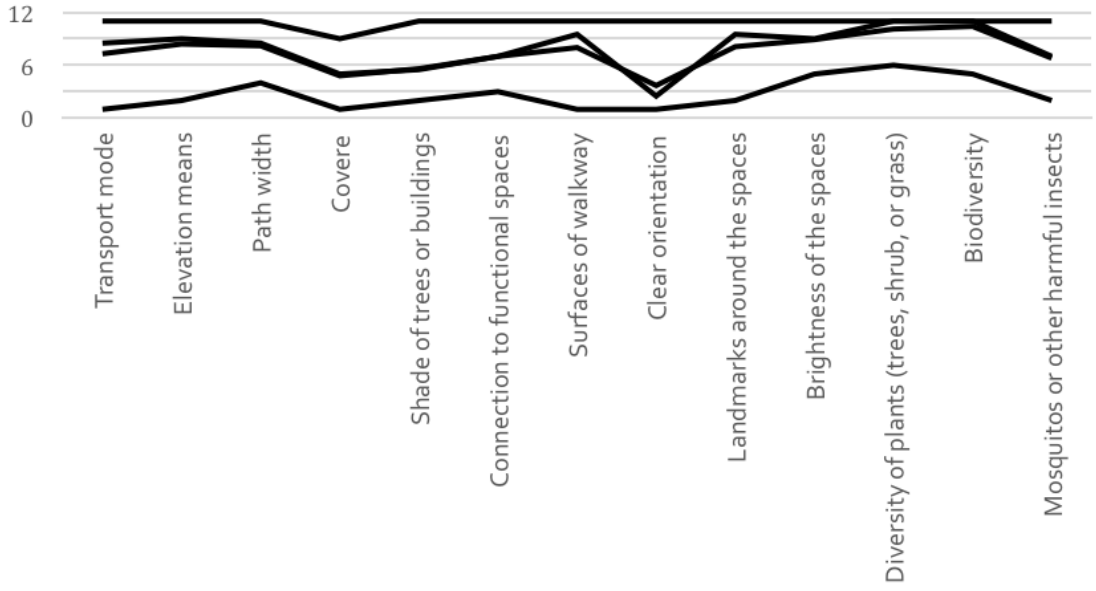

Figure 13 - Ranks of environmental factors based on survey in Punggol Waterway Terraces I. The lower the grade, the more important the factor is.

Meanwhile, some interesting phenomena were also observed:

- Paths without shade or with only tree shade were more attractive than those with building shade.
- There is a robust correlation (r=-0.547, significance <0.001) between pedestrian flows and mosquitos and harmful insects.

The importance of the above environmental factors to pedestrians in Punggol Waterway Terraces I was ranked through the onsite survey by residents (Figure 13). It is clear that the environmental factors that concerned pedestrians most are the clear orientation, cover and shade of paths, with mosquitos or harmful insects, and the connection to functional spaces such as playgrounds and fitness corners. People also considered whether or not the path was also used by other transport means, whether or not it was easy and comfortable to walk through (surface materials, the width of the path, brightness and orientation). Well, people considered comparatively less the diversity of the surrounding plants, birds and butterflies.

These rankings helped explain some phenomena related to the path choice in the precinct. For instance, the importance of clear orientation can lead people more to the paths that are partly covered or not at all, or the paths with mosquitos. However, certain conflicts between observation and the surveys appeared. For example, transportation mode, biodiversity, path width and surface materials were ranked much less important than observed in the field study. This might suggest that pedestrians didn't realise the importance of these environmental factors when they choose the routes or might be partly due to the relatively small survey sample size. We postulate that with a large sample size, the inconsistency between users' preference of environmental factors and their actual choices will reduce.

4. DISCUSSIONS AND CONCLUSIONS

The goal of this paper is two-fold. First, we aim to investigate whether pedestrian movements at the precinct scale in Singapore can be predicted by spatial configuration based on analysis such as axial map analysis and angular segment analysis. Second, if the space configuration does not (at least not solely) determine pedestrian movements at the precinct scale in Singapore, we aim to present an alternative explanation of pedestrian movements and route choices from the perspective of physical environmental factors.

By space syntax analysis, we found that pedestrian movements and route choices on the precinct scale in Singapore can be partly predicted from space syntax studies. The predictions by angular segment analysis were closer to the actual pedestrian flows than those by axial map analysis in the studied cases, which is consistent to the previous literature. All these findings demonstrate spatial configuration influencing actual pedestrian flows to some extents. However, based on our GIS-based analysis spatial configuration or patterns cannot completely determine actual precinct-scaled pedestrian flows although both studied sites have relatively high intelligibility. This is partly due to the walking motivations of precinct-scaled pedestrians differing from those in the urban scale.

On the other hand, the differences between space syntax analysis and actual pedestrian flows indicate that environmental factors (rather than space configuration alone) play important roles in the underlying process of path choices, in particular on the precinct-scale spaces. Via interviews and surveys, we found that Singaporean's primary concern when choosing a route within a precinct is clear orientation, cover, shade, connection to functional areas, and whether or not there are mosquitos and harmful insects around the path. It is interesting to notice the differences between people's conscious concern (the survey results) and subconscious actions (the actual pedestrian flows). This will be further investigated in the future study by a large-scale survey.

With regard to the comparison between the two precincts, it is worth noting the differences at the aspects of household demographic background, facility provision and urban connectivity. These three factors, in some degrees, may also affect the interactions between residents and

precinct spaces, and furthermore impact the influences of each spatial factor on pedestrian flows. For instance, living in an isolated precinct as The Interlace with plenty of facilities, pedestrians tend to move more within the precinct than frequently transit between the precinct and the outside areas, compared to those pedestrians living in relatively more accessible precincts with fewer facilities as Punggol Waterway Terraces I. They might concern landmark and urban infrastructure less than those people living in relatively open precincts with fewer facilities. This important characteristic of pedestrian movement distinguishes our current research with many other studies on pedestrian flows. Whether and how these demographic background, facility provision and urban connectivity impact the pedestrian movements is a question that requires further study.

we must admit that the current paper primarily focused on one site, Punggol Waterway Terraces I, as there were obvious differences between the axial map analysis and the actual pedestrian flows of Punggol Waterway Terraces I, as shown in Figure 7 and Figure 9. The study is still ongoing with respect to observing pedestrian movement, quantifying difference between space syntax analysis and actual pedestrian flows, and conducting surveys on route choices. With the increasing amount of information and survey responses, the findings may be more precise. Meanwhile, other space syntax analyses such as visibility graph analysis (VGA) will be implemented to study the effect of spatial configuration on pedestrian movements and route choices.

Although limited in case studies, the results in our current study are quite promising as a variety of physical design factors such as path surface materials, landmark, and mosquitos or harmful insects are found to significantly influence pedestrian flows in precinct-scale space in Singapore. Our findings shed new light on the effects of physical design factors on pedestrian movement and route choices.

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