

“Doing, thinking, feeling home” - 14/15 October - Delft, The Netherlands

Analysing Mental Geography of Residential Environment in Singapore using GIS-based 3D Visibility Analysis

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Abstract

Residences' mental perception, especially spatial perceptions of their built-environment is crucial in shaping their overall quality of life and environmental perception. The increasing intangibility of mental geography may be caused by lack of empirical and quantitative approach. We will introduce an empirical and quantitative approach of analysing mental geography, based on James Gibson's direct perception theory. Gibson argued that spatial perceptions of the visible environment were constructed by ambient optic arrays, or photonic arrays reflected by environmental geometries and received by perceiver's eyes. We've developed a GIS (geographic information system)-based 3D visibility analysis, Viewsphere, capable of computing the spatial properties of ambient optic arrays, based on the volumetric amount of space occupied by the photonic arrays. Using this analysis, the perceptual quality of residential or urban open space can be measured. We argue that the spatial properties expressed by quantitative perceptual indices may represent the residences' spatial perception of their residential environment. Comprehensive understanding of a residential setting's mental geography may be achieved by mapping of spatial perceptions through interpolating perceptual indices from a grid of sample points. Two test cases were conducted on an environmental setting of typical Singapore's public housing estate. Singapore's public housing programme is well-known for its success of housing most of the nation's population in its high-density, high-rise environment. Using this analytical methodology, the impact of high-density, high-rise residential environment on residence's mental geography can be empirically understood.

Keywords: Spatial perception; ambient optic array; 3D visibility analysis; public housing

1. Introduction

The idea that the human mental perception of the living environment is structured by urban form or urban spatial configuration has been a common proposition taken by urban researchers and urban and landscape designers for decades (Lewis, 1964; Lynch, 1976; Appleyard, 1975; Benedikt, 1979; Hillier, 1996; Batty, 2001; Llobera, 2003; Teller, 2003). It was suggested that the complex human perception, cognition or spatial behaviour may be related to some simple physical properties of the environment. The proposition implies that human perception is influenced or to certain degrees can be manipulated by reconfiguring physical urban form. The process of spatial and environmental perceptions occurs when urban form is perceived by human

visual apparatus and nervous system, by which through cognitive process human can have psychological preferences. The geographical distribution of human mental perception is the focus of the study of mental geography. Mental perceptions that can vary geographically or spatially are definitely the ones that are closely dependent only on the physical, geographical or environmental settings, and they are commonly known as spatial perception. There are wide varieties of spatial perceptions such as visibility, openness, enclosure, spaciousness, spatial definition, scale, perceived density, and daylight perception. Since the way human perceive the geographical environment is through visual senses, sometimes the term spatial-visual perception is used to accentuate the visual component. In the case of residential environment, especially in urban areas, several characteristics may affect spatial perceptions, such as geometry of built-environment, which is the basis of our analysis of mental geography. Other factors, such as microclimate, lighting, colour, or social settings are not within the focus of this study.

There are two methodologies of analyzing mental geography based on the spatial-visual analysis theory, which belongs to 'general' normative theory of geographical space, such as urban space, consisting of user psychological preference and formal normative theories (Lynch, 1981). User psychological preference theory studies the psycho-physical realm, on emotional effect responding from physical environment stimuli, exploring abstract values of the connotative meaning of space. Formal normative theories, of which this study belongs to, study the formal quality of spatial setting, looking to the visible and geometrical characteristics which may affect spatial-visual perception, exploring the denotative meaning of space. Formal normative theories can be classified based on each of their concerns and foci. Some theories focus on essential *variables (indicators, indices, or metrics)* which may affect and may represent visual *perception* of living environment, i.e. scale, visibility, and enclosure-openness (Lynch & Stephen, 1965, 1972). Other theories focus on *critical characteristics* shaping the *cognition* of the structure of spatial forms, such as continuity, regularity, order-disorder, and complexity-simplicity. We will study primarily the theories focusing on *indicators* such as scale, visibility and enclosure, and the possibility to develop a new custom-made visibility analysis based upon it.

Spatial-visual perceptions generated from environmental surface and geometry, which reflects, refracts, and absorbs radiation, is the focus of this research (Thiel, 1996:133). Human perceptions of space and environment are always subjective to each individual, which hold different anatomical, ecological, educational and social backgrounds (Harvey, 1973). However, researchers have argued that a consensus of similar perception in a social group may occur, which can be the basis for researching "collective perception" or "collective mental image" of the urban environment (Thiel, 1961; Lynch, 1960).

There are qualitative and quantitative dimensions of spatial perceptions. Quantitative dimension was observed extensively by environmental psychology tradition. They have revealed that there are quantitative indicators useful for understanding spatial perceptions, using computational visibility analysis such as isovist and viewshed as the perception's quantifier (Batty, 2001; Yang and Putra, 2003). Some of these studies argued that their preference in quantitative approach gives them satisfaction to their beliefs of mathematical certainty in the perception of living environment (Turner, 2003). However, quantitative approach has also been criticized by its counterpart, as being too 'naïve'. Certainly there are limitations of quantitative approach, especially concerning human environmental psychology. As argued by Fisher-Gewirtzman, "architecture and urban design are too complex to be understood by quantitative metrical analysis" (Fisher-Gewirtzman & Wagner, 2003). But even the complexity itself is not contradicting with development of analysis tools to overcome it, as history has shown that space-related studies have always developed methods to analyze space by reducing the complexity into "useful and manipulate-able abstraction." The existence of both quantitative and qualitative

dimensions gives indication that understanding visual perception of urban space can never be comprehensive without presenting both approaches together. In a deeper inter-relationship, quantitative indicators may represent *partially* spatial (qualitative) characteristics, and by representing it with more indicators, a more accurate understanding will be achieved in the process.

The original concept of visibility analysis came from Gibson's psychological theory. Gibson's theory of direct perception (Gibson, 1974) is one of the prime theoretical foundations to develop visibility analysis. Direct perception regards the relationship between the occupant and the environment, rather than attempting to gain access to the vernacular phenomenological idea of perception. Gibson has further developed his theory of ecological visual perception with the *ambient optic array* (Gibson, 1986). As was discovered by Owen and his team, our eyes, or precisely our retina, perceive visual signals from arrays of photon ambient of our position in the environment through process of estimation, instead of identification. The retina estimates the signal transferred by photon arrays, or ambient optic arrays in Gibson's term, then transmits them to our brain cortex, collectively for generating our visual perception. The theory of photos shows that there are ways to measure visibility through measuring the amount of the packaged energy such as 'brightness' or 'radiation' (Owen, 2004). Apart from being energy bodies, photon arrays was described simply as spatially existed and spatially measurable entities in Gibson's description of ambient optic array (Gibson, 1986). In the context of measuring urban environment, we argue that the spatial properties of 'visible space' (in relation with urban and environmental space) can be defined and measured from the collective amount of geometric Cartesian space occupied by photon rays or ambient optic arrays reflected by physical surfaces and visually perceivable from a particular vantage point. This definition implies the potential of developing an approach of quantitative visibility analysis in a three dimensional way.

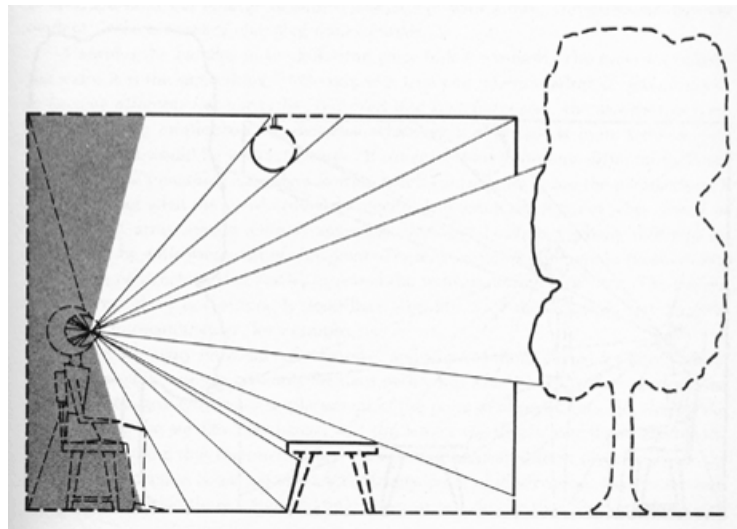


Figure 1 Ambient optic array from a person's visual system (Gibson, 1986)

Batty (2001) stated that the actual physical morphology of complex urban building and streetscapes cannot best be measured by the geometry itself, but is more likely to be represented by the visual 'objects' or 'visible spaces', which is Gibson's ambient optic array emerging as a result of this geometry. This statement has expressed the basis principle for two- and three-dimensional analysis. The impact of visual field or ambient optic array for human perception is already well known, and so it's natural that much effort goes into using, and trying to predict the impact upon visual or spatial perception. Awareness, whether unconscious or articulate, of visual

qualities and lines of sight has been part of human activity, settlement building, military defence, hunting, and agriculture since prehistory. It indicates that we should evaluate the potential visual impact of the existing and proposed urban

The term 'visibility' has been used casually by so many disciplines, implying to different meanings that sometimes are not identical or even correlated at all. This is an example of a popular definition of 'visibility': "the ability to view or the viewing quality of an object or scenery which is affected by atmospheric quality." In aviation and navigation, 'visibility' is used to refer to the distance of unimpeded visual range, because of atmospheric factors, as in 'visibility of 1000 meter. In lighting studies visibility relates with 'glare', or lighting indicators such as 'lux.' Psychological and philosophical meanings of visibility, as implied by the English term 'to see', may imply 'to understand', instead 'to view.' These meanings will not be discussed in this dissertation, although they are relevant factors which contribute to the totality of human visual perception of urban space.

The term 'visibility' in this dissertation primarily relates to the 'visible' or 'invisible' status of a point or location from a vantage or observation point. Thus, when there's no obstructing object that hinders the Line of Sight (LoS) between the vantage point and the target point, it is considered 'visible'; otherwise it is 'invisible.' The secondary meaning of 'visibility' in this paper relates to the question "how much can you see" which queries the quantitative aspect of visibility. This definition concerns with the objective calculation of visibility, which is quantifiable based on optical science of ambient optic array and trigonometric-volumetric calculations. The viewer's mental and physical states are determinants of the perception as much as the physical layout and optics of the situation (Gibson, 1979). That visibility is part of a sequence is especially important in architectural and landscape design and planning, because the sequence of spaces, structures, and views can be controlled and manipulated.

The study of empirical analysis of perceived visual quality of urban space has started from mid-20th century (Kilpatrick's, 1954; Wohl & Strauss, 1958). The mental geography techniques of visibility analysis in urban space can be traced back to the city design tradition (Cullen, 1961; Lynch, 1976; Bosselmann, 1998), such as sequential order technique of analysing visual experience, focusing and studying particularly on town scale (Cullen, 1961). Kevin Lynch (1960) developed his legibility theory based on visual identification of urban elements, but later expanded it further in experiments on regional sense management, in more practical methods. He explored more than 20 mapping techniques of analyzing "sensuous" information. Some of those spatial analysis techniques are visual guidelines development, analysis of legibility, visual corridors, figure-ground (a technique originally developed in 18th century), spatial structure of space & visual axes, sections, isometric view, time envelopes, etc (Lynch, 1976). Techniques such as visibility (viewshed) and sequential views similar to Cullen's picturesque townscape were developed (Lynch, Appleyard & Myer, 1964). They expanded the approach further through varieties of experiments and suggested that we should prepare a framework plan that locates major viewpoints, corridors and view fields with the specification of their desired quality and shows what is to be saved and what is to be created. At that early stage, Lynch has already realized that there is a need of computer systems for delineating view fields, creating diagrams of intervisibility and view access and defining the classification of districts through the relative "eye range" (Lynch, 1976).

The basic idea of connecting objects by straight Lines of Sight ('rays') from a viewer position ('eye-point'), at the heart of viewshed analysis, is the same geometric technique used in architectural rendering by so-called 'ray tracing'. Line of Sight (LoS) is the foundation of most visibility analysis. In recent GIS applications, the viewshed can also be defined as the grid cells in

a digital elevation model that can be connected by means of LoS to view point within any specified distance. The development of computer hardware and efficient algorithms for performing what is essentially a repetitive calculation has made the possibility of performing visibility analysis, in reasonable time on ordinary computers. The visibility analysis tradition has been dominated by two types of two-dimensional analyses, the concept isovist in architectural and urban space and the concept viewshed in terrain and landscape analysis. Compared with isovist which is usually a two dimensional bounded polygon, the GIS-based viewshed analysis is a 2.5D concept.

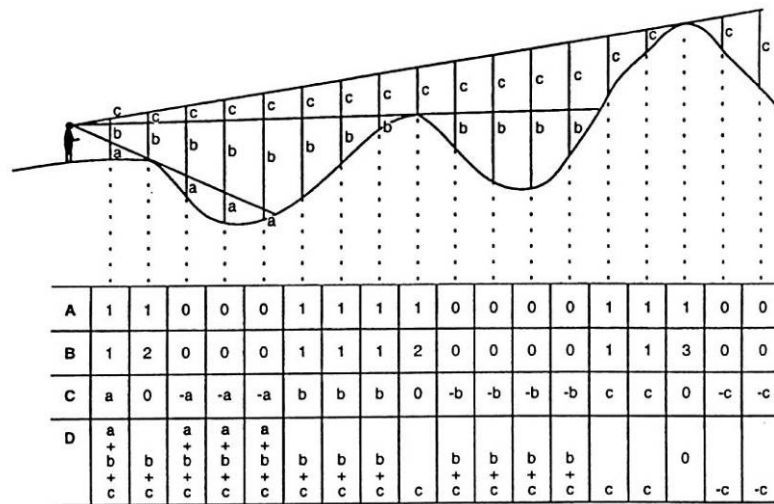


Figure 2 Line of Sight (LoS) studies on visibility and archaeological significance using GIS-based algorithm to provide richer information about local (B-2) and global (B-3) horizons and local (C) and global (D) offsets (Fisher, 1995)

The notion of isovist was first mentioned by Tandy in 1967, which was further developed mathematically and computationally by Benedikt (1979). The isovist or isovist plane is defined as the set of points in 2D space that are visible from a vantage point. With different research agenda from Lynch's urban design tradition, Benedikt suggests a more easily quantifiable and susceptible way to scientific study (Benedikt, 1979). He developed the way of measuring the shape of isovists through calculating the area, perimeter, occlusivity, variance, skewness, circularity and other indicators. The shape of isovists thus may imply certain perceptions, such as view control, privacy, defensibility, and dynamic complexity. Benedikt and Burnham (1985) went on to consider the complexity of isovist properties on perception, aiming for the perceived values of 'spaciousness', a similar idea with 'enclosure-openness' (Turner & Penn, 1999). Benedikt's researches are among the first to relate visibility analysis with behavioural and perceptual studies. Some recent researches applied similar ideas to the analysis of architecture and urban space such as gallery, house, street and town center (Batty 2001, Turner et al. 2001). Others applied and developed isovist for intervisibility computation (Hillier and Hanson, 1984; O'Sullivan & Turner, 2001), for visibility graph analysis on TIN data format (De Floriani et al, 1994). Behavioural impact of visibility was also studied on pedestrian's wayfinding (Conroy, 2001), and on public space's surveillance to improve public safety.

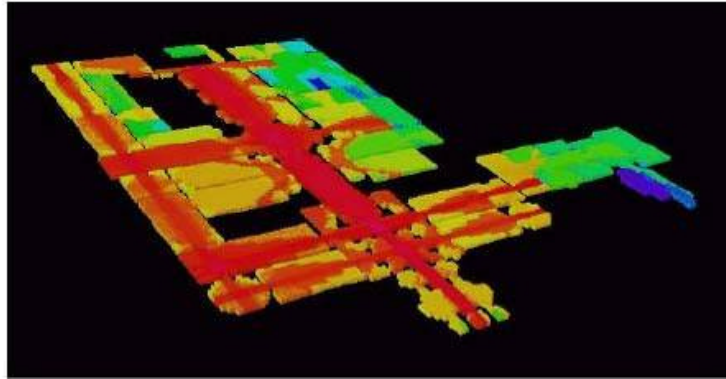


Figure 3 Isovist application for Virtual Tate Gallery, London (Batty et al., 1998)

Architectural theorists in the 1980s developed the technique of viewshed with respect to architectural spaces and floorplans, following Benedikt's work (1979). The term 'viewshed' is an analogy to the hydrologic watershed (Felleman, 1979). The viewshed analysis is another traditional way of analyzing visibility field, which can be described as the landscape terrain visible from a major viewpoint (Lynch, 1976). The viewshed was also defined as "the cells in an input raster that can be seen from one or more observation point or lines", and the cells are given the value 1 otherwise zero (ESRI, 2004). Viewshed originated from the landscape studies of Amidon & Elsner (1968), and Lynch (1976). Recent studies were usually conducted on GIS platform, such as classic analysis of mountainous area (He & Tsou, 2002; Figure 4), in relation to the height of origin and target points (Fels, 1992), to types of path preferences (Lee & Stucky, 1998), and for archaeological studies (Wheatley, 1995; Fisher, 1995; Fisher et al., 1997; Lake et al., 1998). Cumulative viewshed is a matrix of viewshed values contained in points, producing a raster-like representation. Visualscape is another extension of viewshed, which is defined as the 'spatial representation of any visual property generated by, or associated with, a spatial configuration', and contributing new indicators such as of visual prominence in space, visual exposure (Llobera, 2003). The viewshed analysis in GIS is hardly applied in urban settings because the operation is based on raster data or TIN (triangular irregular network) data structure, which are not very supportive for modelling high-resolution 3D urban model. There is an absence of GIS procedure which can integrate terrain and built environment (Llobera, 2003).

Quantitative indicators derivable from the formal geometric characteristics were hypothesised to be useful for understanding mental geography of urban living environment. Quantitative indicators may represent *partially* spatial (qualitative) characteristics, and by representing them together with more indicators, a more complete picture of the characteristics will be achieved in the process. There are two types of quantitative indicators presented below, which are Euclidean indicators and field-based indicators. Euclidean indicators include fixed distance-based indicator and proportional indicator. They are Euclidean indicators, because they are direct adaptations from distances towards surrounding Euclidean geometrical form. Field-based indicators include two-dimensional and three-dimensional indicators. Several Euclidean and field-based indicators have been studied in relation with spatial perceptions, particularly perceptions of enclosure, visibility, and scale.

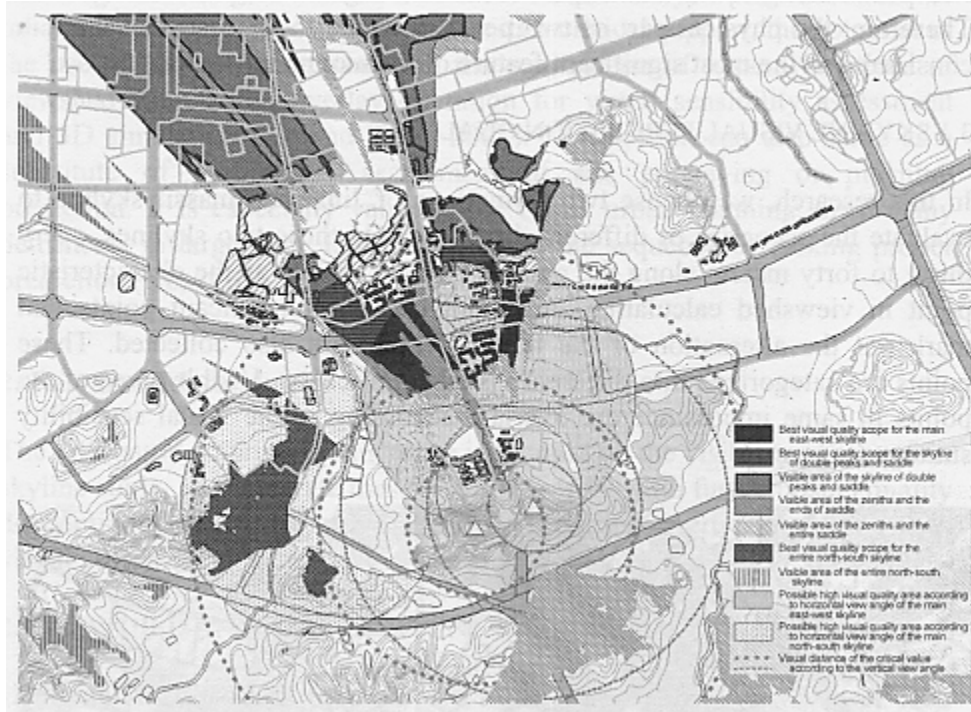


Figure 4 Visual quality mapping of skylines by overlaying viewshed analysis and human visual ergonomics and psychology parameter analysis (He & Tsou, 2002)

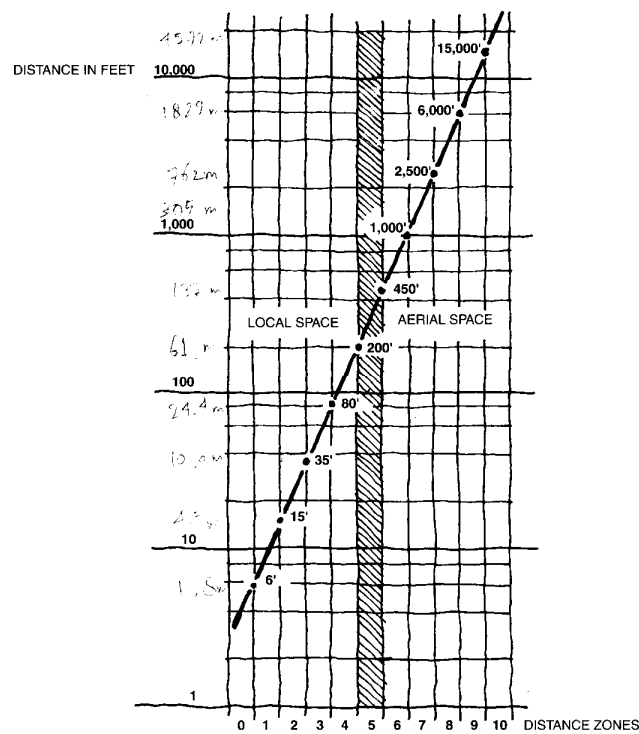


Figure 5 Spreiregen's (1965) classification of perception of scale

Distance-based indicators have been studied in relation with spatial perceptions, particularly perceptions of *scale*. Spatial indicators were investigated in relation to scale (Blumenfeld, 1953; Hedman & Jaszewski, 1984; Gehl, 1996). Earlier indicators classified perception of scale simply as ‘aerial (global) space’ and ‘local space’ (Gibson, 1950; Sitte, 1889; Jacobs, 1961), which was later refined to more detailed distance-based classification (Figure 5: Spreiregen, 1965; and Thiel, 1996:209). A more human-based scale indicators was later formulated (Gehl, 1996), influenced by human-based spatial behaviour dimension (Hall, 1966).

Proportional indicators have been studied widely in relation with spatial perceptions, particularly perceptions of *scale*, *visibility* and *enclosure*. In the case of scale, height-to-width and height-to-length ratio was proposed, (i.e. 1:4, 1:2, 1:1, and 3:2) (Hedman & Jaszewski, 1984). Indicator for visibility was discussed in relation to by). Visibility were discussed much in relation to the vertically angular (β) projection of LoS between observer and obstruction point or the highest and farthest visible point along LoS, which is easily translated to distance-height (D/H) proportion (Lynch, 1962; Spreiregen, 1965; Higuchi, 1983:46-49; Hegemann; 1988:42-50). The vertical angle β is equal with the concept of solid angle, which is subtended by a hemispheric surface is defined as the surface area of a unit sphere. The perception of enclosure, which is principal in human occupation of space, was also discussed in relation with proportion of space, (Spreiregen, 1965:75; Maertens, 1877, in Blumenfeld, 1953:36-37). Table 1 below shows the referred works on enclosure using the D/H proportion of side faces view. It’s very clear that D/H proportion and solid angle β have very clear relationship with enclosure indicator. Enclosure norms from Spreiregen (1965), Lynch (1962), and Ashihara (1983) show easily identified resemblances.

According to these writers, indicators for perception of scale, visibility, and enclosure are much related to two-dimensional distance and proportion between observer perpendiculars to the nearest surface. When applied to three-dimensional irregular urban form, the question is to which direction the distance or proportion should be derived from. This problem brings up the limitation of traditional two-dimensional indicator in representing three-dimensional spatial perception of urban spaces with irregular geometry. In order to perform the 2D indicators, presumed conditions of geometric regularity and continuity, well-known as infinite straight urban canyon (Oke, 1987; Figure 6), must be met. An expanded form of three-dimensional viewshed, or isovist, analysis for permanently solving this limitation is definitely lacking (Ervin & Steinitz, 2003).

Table 1 Perception of enclosure comparison with vertical angle (β), D/H ratio, and VSI

β (vertical angle)	H/D ratio	Spreiregen, 1965	Lynch, 1962	Ashihara, 1983	Viewsphere Indices
45	1 : 1	full enclosure	full enclosure	balance of enclosure	0.7071
27	1 : 2	threshold of enclosure	comfortable enclosure	expansive space	0.4472
18	1 : 3	minimum enclosure	comfortable enclosure	comfortable enclosure	0.3162
12	1 : 4	‘losses’ its enclosure	enclosure ceases	enclosure ceases	0.2425

Preceding 2D visibility analysis tradition has not established successful relationships with human perceptual understanding, since reasonably thorough empirical study has not been conducted to establish them. These 2D analyses mainly offered two-dimensional spatial quantification of photonic arrays, as if photons can only radiate two dimensionally in space. Spatial embodiment, analysis, and representation of ambient photonic arrays have never been accomplished by these 2D analyses. As the result, visibility analysis’ reliance on geometric and trigonometric

calculations of visible spaces has been questioned, and deemed as may or may not reflect what a human viewer would actually perceive. From visibility analysis point of view per se, an expanded form of three-dimensional viewshed, or isovist, analysis are lacking, and may be helpful (Ervin & Steinitz, 2003).

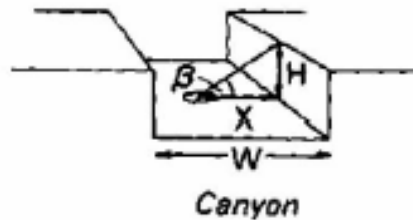


Figure 6 Proportional indicator applicability is limited only for ideal situation of ‘infinite straight urban canyon’ (Oke, 1987)

Efforts to develop 3D visibility analyses were conducted, and providing candidates such as Spatial Openness Index (SOI) (Fisher-Gewirtzman et al, 2003), Sky Opening (Teller, 2003), and Sky View Factor (Ratti, 2001). SOI and Sky Opening were discussed for analysing visibility in three-dimensional way in relation to spatial perception. SOI was not technically operational for large 3D urban models, and its index was computed with an element of ‘approximation.’ Sky Opening’s methodology and algorithm of double projection caused deviation from the actual results. Moreover, they didn’t established relationships with pedestrian direct perceptions through in-depth user survey. Thus, there’s still a need of an operational and proper three-dimensional visibility analysis and indices which can analyse and predict spatial perceptions. We argue that mental geography of residential environment should be better described and analyzed through the computation of 3D visual effects of pedestrians. We hypothesize that changes of mental geography can be manipulated through the reconfiguration of urban form, where the consequences of urban design actions can be predicted quantitatively through visibility analysis of pedestrians.

2. Development of Viewsphere 3D Analyst and Indices

Viewsphere 3D Analyst has been discussed more comprehensively in the previous publications (Putra, 2005; Yang, Putra & Li, 2005a, 2005b), and will be discussed briefly in this paper. The Viewsphere 3D Analyst or Viewsphere in short can be defined as a 3D visibility analysis by calculating the visible ‘volume’ of ambient optic array, or Volume of Sight *VoS*, which is constructed through viewing from a specific observation point to the surrounding environmental obstruction points by the “scanning” of visual line or the line of sight. Viewsphere is originated from the concept of the line of sight *LoS*, which is a basic tool of visibility analysis in GIS. GIS-based Viewsphere 3D Analyst was developed and customized on ArcGIS 8.3 platform using ArcObjects based on Visual Basic language version 6. Viewsphere is designed especially for analyzing 3D urban massing or simple geometrical form, in which the terrain-landscape and urban built environment are integrated and modelled in TIN or raster data. Viewsphere graph is the graphic representation of Volume of Sight *VoS*, a collection of countless vertically stacked ambient optic arrays between the vantage point and all visible points along the line of sight *LoS*, stretching to the horizontally farthest visible point or obstruction point.

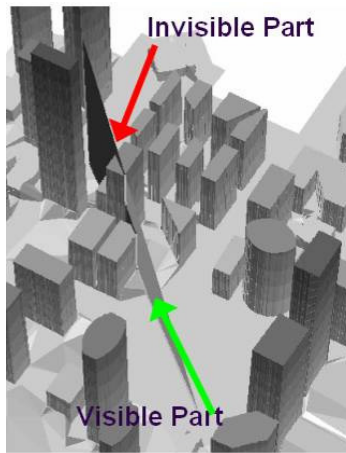


Figure 7 Invisible and Visible parts of line of sight LoS_{ij}

As similar with 2D isovist, which is defined as the ‘space directly visible or accessible from a specific observation point and is often taken as the entire space viewed when moving through 360° or 2π radians’ (Batty & Rana, 2004), the total viewsphere graph can be taken as a specific form of three-dimensional isovist using the 360° or 2π rotation of 3D sight line from a specific observation point. The 3D representation of the total viewsphere graph in 3D GIS appears like a triangular fan (Figure 8). We argue that the total viewsphere graph VS_i as a three dimensional spatial representation is much closer to Gibson’s concept of ambient optic array than the 2D isovist simply because viewsphere graph’s can accommodate 3D spatial properties of ambient optic array and the visibility structure is closer to a 3D spherical field than a 2D plane surface (Gibson, 1986). We limit the application of Viewsphere 3D analysis to the context of intensive urban environment, where the ambient optic array can be computed within a confined visible boundary rather than an unbounded open field. However, the approach will need to be revised when dealing with other urban settings with radical variations of terrain or a significantly prominent landmark from a far and long distance viewpoint.

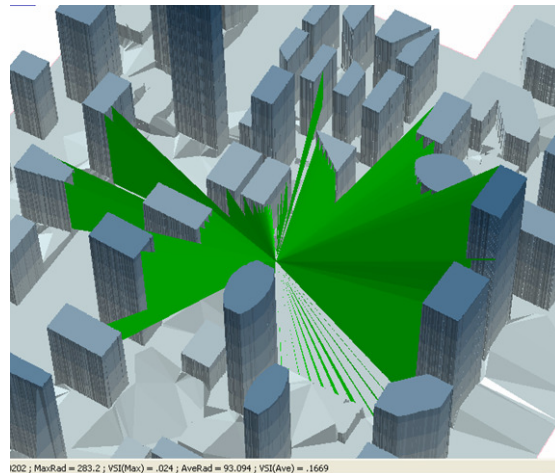
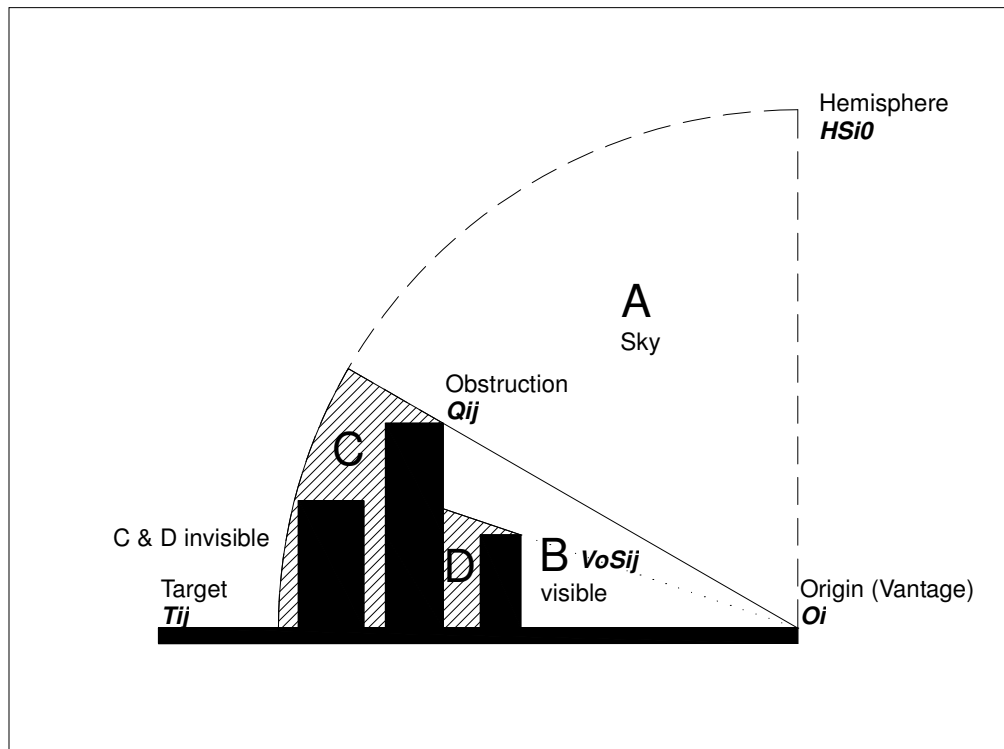


Figure 8 Viewsphere 3D analysis in operation; the radiating ‘rays’ are the viewsphere graph



The spatial volumes of ambient optic arrays can be calculated from: (A) volume constructed from visible sky optic arrays inside the virtual hemisphere; (B) visible volume *VoS* constructed by visible arrays from observation point to the urban and environmental surfaces before the obstruction point; (C) invisible volumes behind the obstruction point and inside the hemisphere, and (D) invisible volumes in front of obstruction point (Figure 9). The volume of sight *VoS*, or the computation of viewsphere graph, provides a GIS-based visibility measure in a three dimensional way as a nominal volumetric index of visible space in cubic meter. The main question is how can we use it for further understanding the 3D spatial characteristics of urban spaces? How do we transform the GIS operation of 3D visibility to effective urban form indices for measuring and comparing the degree of visibility among different urban configurations? For comparing the degree of visibility in different urban settings, we define a 3D urban form indicator *Viewsphere index (VSI)* for measuring the percentage of the visible space *VoS* that fills up the hypothetical spherical view area. *VSI* is a proportional index ranged from 0 to 1, representing the magnitude of certain mental perception of urban environment. *VSI*'s value is much depended on the volume of its virtual hemisphere, which can be controlled by its optional radiuses, such as from a user-defined radius, or its statistical inferences. Thus, two *VSI* readings from the same location with different radius settings will be different as well. To solve this situation in this experiment, we've assigned 'the distance to the nearest vertical environmental surface' as the radius setting for *VSI*.

3. Previous findings on meanings of Viewsphere Indices

Viewsphere 3D Analyst simulates spatial and environmental perception process, when urban form is perceived by human visual apparatus and nervous system, by which through cognitive process human can have psychological preferences. This process involves a stretch of stages of translation,

or rather creation of values, from urban space to human psychological realm. Viewsphere generates Viewsphere Indices (VSIs) functioning as inter-mediators between urban space and its perceptions. Figure 10 describe these ‘valuation’ stages.

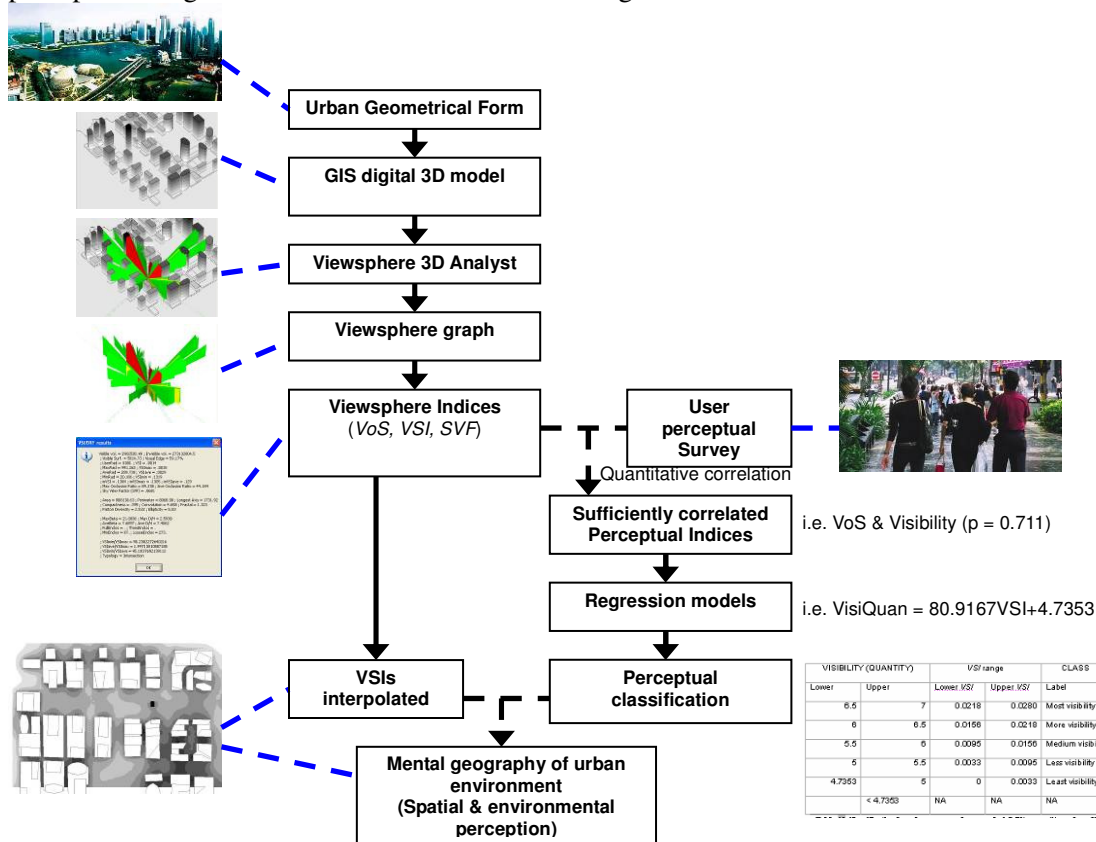


Figure 10 Methodology of analysing urban geometrical form to generate VSIs for predicting spatial and environmental perceptions

First, how could we elicit the mental images of pedestrians’ spatial and temporal perceptions through appropriate techniques and tools? A limited user survey of observers’ perceptions was conducted on five locations in downtown Singapore: Orchard Rd: shopping & tourist area, Tanjong Pagar: CBD, Raffles Place: CBD, Rochor: mixed-use public housing, Chinatown: mixed-use traditional housing (Putra, 2005). The last two locations are residential areas, thus will be discussed thoroughly. 40 architecture students were invited as respondents, and they were asked to walk along designated 300 meters paths on each location, unsupervised. They were given a questionnaire set with a 2D figure-ground map of the designated paths and their surrounding areas. After completing the paths, they were asked to rate from 1 to 7 the quality of urban space they’ve experienced along the path, in terms of: ‘Close – Open’, ‘Confined – Spacious’, ‘Small Scale – Big Scale’, ‘Can see less – Can see more’, ‘Can’t see far – can see farther’, ‘Less defined – More defined’. These questions are each related to perceptions of enclosure, spaciousness, scale, quantity of visibility, distance of visibility, and spatial definition in the same order. The perceptions of enclosure, spaciousness, and spatial definition are grouped within a category of ‘perceived enclosure’, and both perceptions of visibility are also grouped together. Their responses were compared with VSIs from spatial indicators of respective spaces, and their relationships and regression’s predictive models were established from statistical evaluations, such as ANOVA, Pearson’s correlation, linear and curved regressions were conducted. Based on these evaluations, VSIs were presented as valid indices for analysing and predicting mental geography of an urban environment, through defining perceptual classifications

based on eligible predictive regression models.

In this research we did not intend to explore the internal-personal experience or the mental process of the perception of space and time. The psychological analysis of the spatial experiences is beyond the scope of the research. We simply hypothesized that there exist possible correlations between urban form attributes and pedestrians' spatial perceptions. Spatial perceptions in this study constitute of many possible dimensions, such as visibility, enclosure, perceived density, etc. The spatial and temporal perceptions may subjectively vary because of walking speeds, social status of interviewees, gender, ages, social classes and especially the purpose and familiarity. Although these factors may cause different results and need to be considered, discussing them in this paper will be too ambitious. Therefore, the strategy of the research is to get as many samples as possible in the field survey.

We hypothesize that there are significant relationships between visible volumes of urban space with its spatial perceptions of visibility, enclosure, and scale, has been validated. The nature and degree of these relationships have been determined as 'significantly correlated' by ANOVA's significance level p below 0.05, Pearson's correlation higher than 0.5 of 1, and linear or curved regressions R higher than 0.5 of 1. In example, VoS was discovered to have significant quadratic relationships with perceptions of visibility ($R = 0.576$), enclosure (or openness) ($R = 0.652$), and scale ($R = 0.733$). Therefore VSIs, in this case VoS , are proven valid as perceptual indices for spatial perceptions of urban space geometry. Regression diagrams of relationships between VoS and each perceptions are displayed in Figure 11.

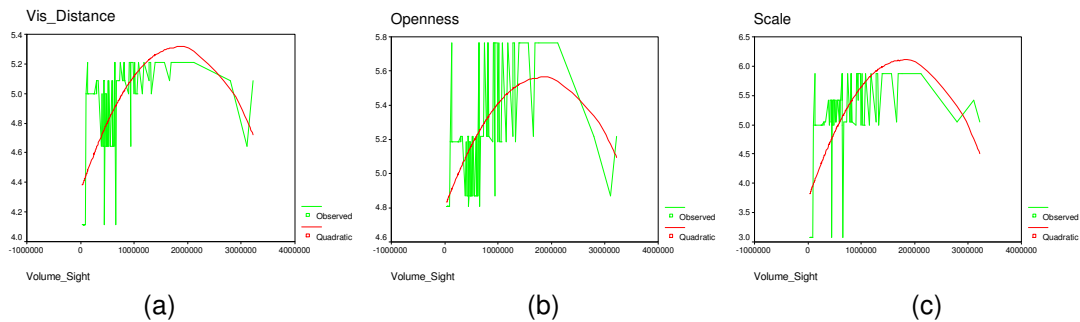


Figure 11 Curve estimations from regression analysis of VoS in relation with perception of (a) visibility, (b) openness, and (c) scale

Higher VoS indicated larger quantity of volume of visible space (in m^3) thus implying observer's higher quantity and distance of visibility, higher perceived openness, spaciousness, and spatial definition, to all horizontal and vertical directions. However, there are optimal VoS values for each perception, where residences are no longer capable to perceive more visibility, openness, or scale. Based on this finding, a predictive regression model of VoS producing a predicted classification for GIS mapping have been defined for each spatial perception. The VoS -based predicted classifications for each spatial perception are available on Table 2 for visibility, Table 3 for openness, and Table 4 for perceived scale.

Quadratic or parabolic relationships were found between VoS and spatial perceptions, signifying that the visible volume of space has more influence on spatial perceptions (of visibility, enclosure, and scale) at smaller volume, and the influence lessen with increasing volume, until a certain value of where greater volume no longer make any difference to the spatial perception. This finding is consistent with the observable phenomena of 'diminishing perception', which imply that human perception of space is more accurate in the nearest distance to human's eyes, and become less accurate with increasing distance from the eyes. In example, we can easily 'measure' precisely the distance between two objects located a few meters from our position, but

we will have difficulty to perceive the distance between two ships located far away in the horizon, even though they are few kilometres apart. Our spatial perception of the two ships which are kilometres apart, in terms of visible distance, will not be much different.

Table 2 Predicted classification of visibility and predicted VoS (rounded to thousands m³)

VISIBILITY (QUANTITY)			VoS range (m ³)		CLASS
Respondents answers (1 to 7)					
Lower	Upper		Lower VoS	Upper VoS	Label
5.636	NA		2229000	NA	Most visibility
5.5	5.636		1449000	2229000	More visibility
5.25	5.5		8855000	1449000	Medium-more visibility
5	5.25		491000	885000	Medium-less visibility
4.75	5		170000	491000	Less visibility
4.6013	4.75		0	170000	Least visibility
	< 4.6013		NA	NA	NA

Table 3 Predicted classification of openness-enclosure and predicted VoS (rounded to thousands m³)

OPENNESS			VoS range		CLASS
Respondents answers (1 to 7)					
Lower	Upper		Lower VoS	Upper VoS	Label
5.682	NA		2061000	NA	Most Open
5.5	5.682		1145000	2061000	More Open
5.25	5.5		630000	1145000	Medium Open
5	5.25		253000	630000	Less Open
4.8003	5		0	253000	Least Open
	< 4.8003		NA	NA	NA

Table 4 Predicted classification of perceived scale and predicted VoS (rounded to thousands m³)

SCALE			VoS range		CLASS
Respondents answers (1 to 7)					
Lower	Upper		Lower VoS	Upper VoS	Label
> 5.994			1662000	NA	Largest Scale
5.5	5.994		901000	1662000	Larger Scale
5	5.5		573000	901000	Medium-large Scale
4.5	5		321000	573000	Medium-small Scale
4	4.5		109000	321000	Smaller Scale
3.7164	4		0	109000	Smallest Scale
	< 3.7164		NA	NA	NA

In the case of *VSI*, two definitive relationships have been discovered through statistical and mathematical experiments discussed previously (Yang, Putra & Li, 2005). Based on highly correlated statistical relationships discovered between *VSI* and Gross Plot Ratio *GPR*, which is an indicator of planning and development density, the perceptual index *VSI* may be nominated as the index of ‘perceived density,’ which can be defined as ‘density of built-environment perceived from the perceiver’s visual apparatus when perceiving from a vantage point.’ *VSI* as index of perceived density is applicable only for the variant with radius setting of its hemisphere based on the ‘distance to the nearest vertical environmental surface.’

Since this *VSI* variant was basically operating more as an angular indicator and less as volumetric one, it was not surprising when we discovered that *VSI* and Sky View Factor *SVF*

have perfect inverse correlation. *SVF* was an established indicator commonly use for urban environmental and climatic studies, and in our case, it was employed as indicator for daylight exposure (Oke, 1987; Ratti, 2001). This contributes in the area of urban spatial analysis and also urban climatology, providing proof that *SVF* can be generated through different approach and different methodology than the original *SVF* calculation (Ratti, 2001). It may be possible that daylight exposure, microclimatic factor and visibility are closely inter-dependently related, in the way that increasing perceived density will decrease daylight exposure and vice versa.

4. Case studies: Residential environment at Rochor and Chinatown districts

Prior to the national HDB housing programme in the late 1960s, Singaporeans lived mainly in traditional colonial buildings well-known as 'Chinese' shophouses in downtown 'Chinatown' commercial district (Figure 12: B). This housing typology is unique to South East Asian region, with rectangular plan, 4-6 meters width and 30-40 meters or longer length, and 3 to 4 stories height. The ground floor was primarily for commercial uses, and the residences lived on the upper floors. Up to six low income family units usually stayed in these shophouses, thus their conditions were degenerated rapidly; the building conditions become unsafe, full with health, sanitary and safety problems because of overcrowding. There is almost no open and green space left in the old Chinatown, since wherever space left will be invaded by street hawkers. The space typology is mainly dominated by narrow streets, and traffic was a problem at that time.

Singapore government took a radical policy and implemented it strongly in the early years of its independence in 1965, to solve and 'clean up' the downtown living environment from these problems, by relocating the residences out from the problematic areas into the new Housing Development Board (HDB) estates (i.e. Figure 12: A). Since then, the policy has transformed the downtown urban slums to highly-valued commercial shophouses, with uses ranging from antique shop to pub and restaurants. Chinatown district today is purely a commercial district, surrounded by new commercial zones of office towers and shopping centres, and there are only few populations reside in the shophouses, since most of the population has been relocated to the newly developed estates or the more affluent ones to private residential developments.

The HDB housing programme was started in the late 1960s, following government policy to solve poverty, overcrowding, health and environmental problems in Singapore's downtown living environment. The housing programme was successful and it's well-known for housing more than 85% of the nation's population in its high-density, high-rise environment. HDB has ever since maintained uniform quality of housing environment throughout Singapore, where residential environment is heavily regulated. HDB's strategy has ever since adopted high-density, high-rise residential typology all over Singapore, mainly because land scarcity is the main issue in Singapore's planning paradigm, being an island-state of not more than 700 km². The strategy implemented gross plot ratio (GPR) from 2.8 to 4.2 at the beginning, and increasing ever since. To maintain visual and environmental quality, all HDB blocks are designed with more open spaces and green areas are set aside in the centre and perimeter of the blocks. Pedestrian and public transportation modes are dominant in Singapore, especially in HDB estates, thus sufficient roads and pedestrian paths are designed properly in the HDB estates. Commercial uses are only allowed scarcely in the ground floor of the blocks. Using this analytical methodology, the perceptual impact of HDB's high-density, high-rise housing strategy on residence's mental geography in comparison with traditional shophouses can be empirically understood.

The policy has also encouraged the real estate development from the private sector since the beginning of the implementation, starting from the high-rise development of the downtown area.

Two private developments in Chinatown, People's Park Complex and People's Park Centre are among the first of their kind, built in early 1970s. Their typical arrangement of floor usage is commercial uses in the first 3-5 'base' floors, and residential uses for the 'tower' floors. The lift access to the higher residential floors is often from inside the commercial floor at ground level. They are usually developed on very accessible and prominent sites, next to major streets and avenues and visible from many directions. Private developments with this arrangement are mostly found in downtown area, or 'the City' as Singaporean referred it, and those outside are mostly for sole residential use. The majority of private residences is high-rise high-density, driven by developer's motive for maximum land efficiency. Thus the less-regulated earlier private developments desperately lack open spaces and green areas, since they were designed for maximum efficiency with very high building coverage.

All these public and private developments has radically changed Singapore's downtown following various government policies since 1960s, implemented by the Urban Redevelopment Authority (URA). The policies redistributed downtown's high population and pedestrian density, while maintaining the vibrancy and economic vitality of particularly its Chinatown area. Public services, such as public transport was vital to the success of this policy, maintaining links between the old downtown with the new HDB blocks.



(A)



(B)



(C)

Figure 12 Residential environments in Chinatown: (A) Public HDB housing at Hong Lim Complex (B) private low-rise housing of traditional shophouses (C) private high-rise housing, Pearl Centre on the left and People's Park Complex on the right.



Figure 13 Relationship between different housing types: (Left: A) HDB blocks and (Right: B) traditional shophouses, with a market in the middle

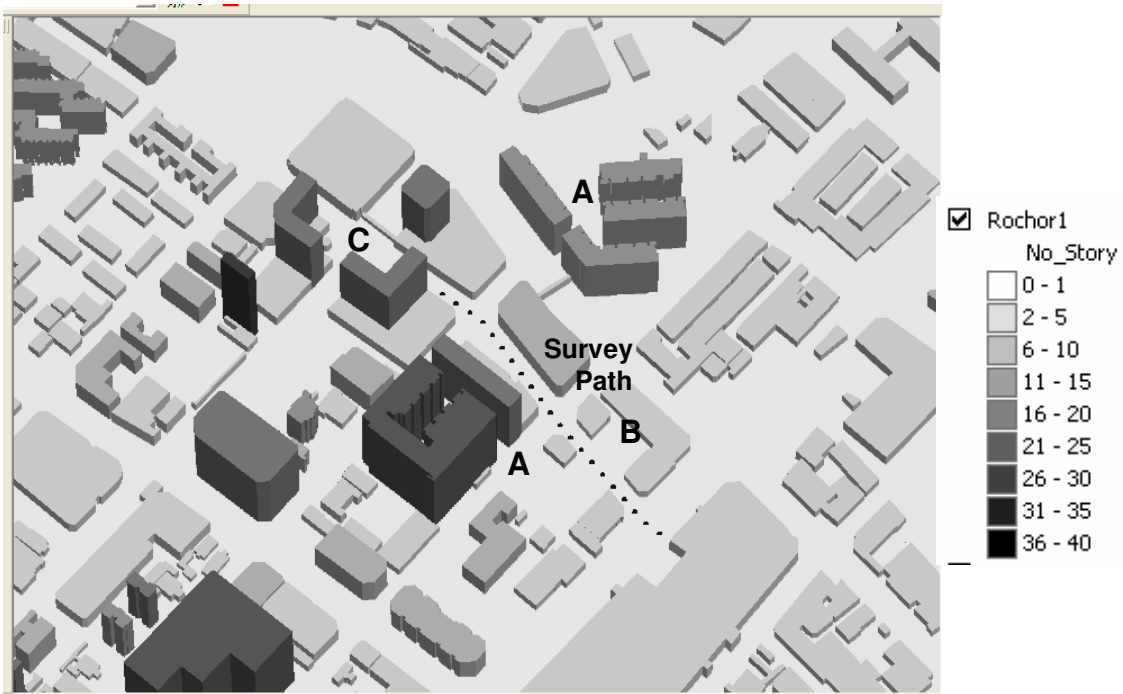


Figure 14 Rochor district residential environment (A: HDB blocks; B: traditional shophouses; C: private apartments and condominiums; with 300 m survey path of previous study (Putra, 2005))

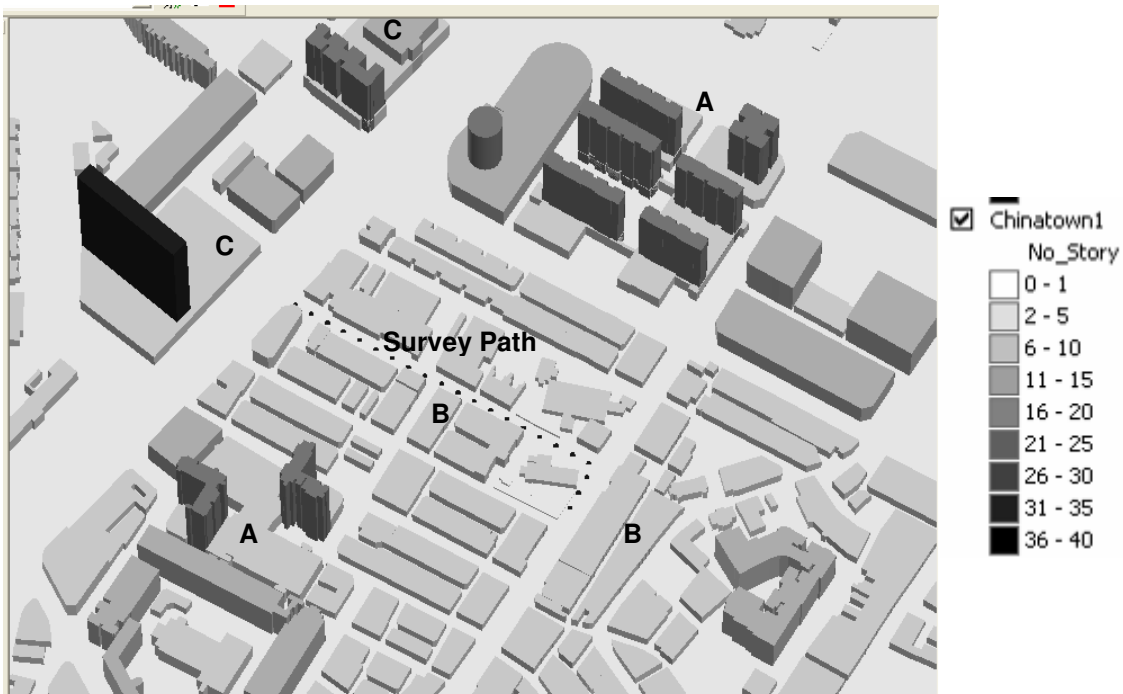


Figure 15 Chinatown district residential environment (A: HDB blocks; B: traditional shophouses; C: private apartments and condominiums; with 300 m survey path of previous study (Putra, 2005))

From the mental perception of older ‘relocated’ residences, it has been a radical shift from living in a high-density, low-rise environment to a high-rise environment, in either public or private housing, with towering blocks up to 50 storeys. Similar and more radical shift has also occurred in other Asian cities such as Hong Kong. This study focuses to the difference of spatial perception between older shophouses typology with new typologies of HDB estates and private developments. The perceptual difference, visible from mapping of different typologies’ mental geography, contributes to the understanding of radical mental shift from living in low-rise to high-rise development.

Two cases from the previous test cases (Putra, 2005), the residential environments at Rochor and Chinatown, are discussed in this paper. These locations are typical Singapore’s downtown living environment, where there’s a good balance between public and private housing estates. Contrary to the downtown area, residential environment in the hinterland is dominated by the public HDB housing.

In Rochor district, it has a unique situation whereby public (A), private low-rise (B) and high-rise (C) developments are spatially intertwined. The two HDB blocks (A) are surrounded by commercial zones, traditional market and shopping centres. Their development density is much higher than the private ones, creating an awkward spatial composition. There are few shophouses (B) preserved in this area, but not as much as in Chinatown. The private residences (C) are grouped around the junction next to Sim Lim Square, Singapore’s main electronic centre. The spaces connecting these different types of residential developments are pedestrian streets, mostly occupied by pedestrians and street vendors, creating vibrancy that attracts shoppers and tourists. The district’s transportation access is serviced by Bugis MRT station in the southeastern end of the survey path, which is the main source of pedestrian flow.

There are many similarities between Rochor and Chinatown district, except that in Chinatown the ‘chinese’ shophouses (B) are grouped in the centre, labelled as ‘conservation area’ and ‘tourist area’. As discussed, few populations are currently living in this area. There are also two HDB estates here (A), with very high development density compared to the shophouses, and they are also surrounded by commercial zones, traditional market and shopping centres. The private developments (C), such as People’s Park Complex on the southwest and People’s Park Centre on the northeast are located across a major avenue, totally separated from the ‘conserved’ shophouses. The spaces in the conservation area are mostly pedestrian streets, with limited vehicle access for the two HDB estates. The main access to this district is Chinatown MRT station in the northwestern end of the survey path.

These two cases were modelled in a 2.5D TIN data format (Figure 14 and Figure 15) for Viewsphere application. The GIS-based TIN format may limit the analytical ability of 3D visibility analysis of Viewsphere. This limitation in 3D urban modelling is a classic GIS limitation, even worse in raster format, which until now don’t have a clear solution yet. However, since 3D geometries of urban environment in the urban design scale are less complex, and the use of more complex data format may not change the analysis’ result significantly, we may still use this data format as the platform for this study.

5. Analysing mental geography of case studies

Comprehensive understanding of a residential setting's mental geography may be achieved by mapping of spatial perceptions through interpolating perceptual indices from a grid of sample vantage points. The inverse distance weighted (IDW) interpolation method of mapping reveals spatial distributions of mental geography, in terms of spatial and environmental perceptions. For Rochor and Chinatown cases, a 5x5 meters matrix of grid vantage points was assigned on all urban spaces, only when the relative base altitude is 0. We've tried ViewSphere successfully on vantage points not on urban space but on top of the building, but it'll not be logical since most residences experience their urban environment from ground-level urban space. Average human visual apparatus was modelled at 1.5 meter for each point. The number of Volume of Sight *VoS* segments was set to 180 and maximum radius to 1000 meters for covering 2π radians ViewSphere analysis.

Three of the six spatial perceptions surveyed previously (Putra, 2005) are discussed, 'visibility', 'openness' (or 'enclosure'), and 'scale', which correlations and models with *VoS* have been defined, predicting classifications for mental geography mapping. Two environmental perceptions of 'perceived density' and 'daylight' are also discussed, which are significantly correlated with *VSI* through statistical experiments. Spatial distributions of each perceptions were mapped below using GIS, and they reveal the relationships between perceptions and form-space geometry and typology. Due to incomplete data for Chinatown case, the results of northeastern tip of Chinatown map are not valid and not to be discussed.

The predictive mapping of spatial perceptions in Figure 16, Figure 17, and Figure 18 reveals their relationships with urban space typologies and with residential typologies. Since these perceptions of visibility, openness, and scale are predicted from one indicator only, *VoS*, their mappings exhibited similar patterns but different classifications. Thus a certain *VoS* value may be classified as less visibility and larger scale in the same time. This also implies that spatial perceptions of visibility, openness and scale are actually closely related.

There are several urban space typologies, such as wide streets (boulevard) and narrow streets, spaces nearby building perimeter surfaces, and spaces between buildings nearby, observable in Rochor and Chinatown. In the two districts of typical East Asian cities, street is the main typology, and large plazas are uncommon except the smaller ones inside HDB estates. Major boulevards has medium-less to most visibility, medium openness, medium-small to larger scale and the street's width has significant positive relationship with its visibility, openness, and scale. Spaces nearby buildings may have least to less visibility and openness, smallest to smaller scale, depends on the distance to and the height of the building surfaces. The closer the distance to the building surface, the less visibility and openness, and the smaller scale residents will be perceived. Spaces between buildings nearby, such as the ones surrounded by HDB blocks, narrow streets and hallways between shophouses, usually have the least visibility and openness, and smallest scale.

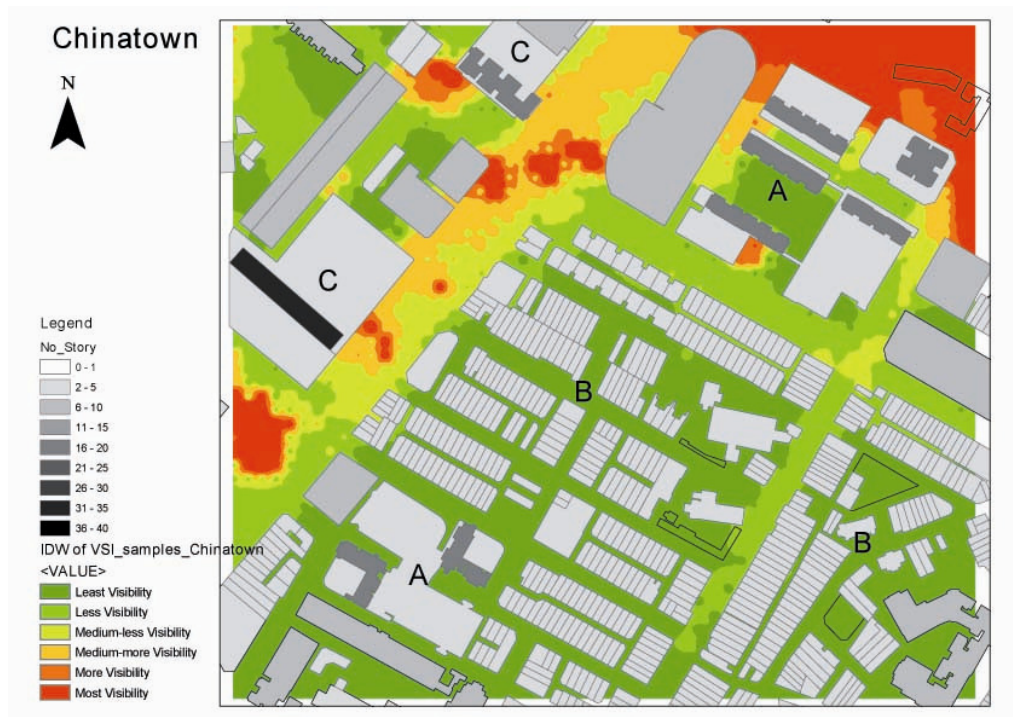
In Rochor, the southwestern areas of the streets have significantly more visibility, openness and larger scale because from this location the skyscrapers at CBD towards southwest direction are visible. For the same reason, more visibility and openness can be perceived along streets aligning to southwest-northeast direction, whereby the skyscrapers are visible, although the perpendicular streets are wider. This finding supports traditional theory of boulevards, such as Haussmann's Parisian boulevard and Camillo Sitte's doctrine of 'visual order' (1889).

Relationships between spatial perceptions and residential typologies' surrounding spaces can be observed. However, perceptions are highly varied on spaces adjacent to each HDB blocks (A), shophouses (B), and private condominiums (C). In example, spaces adjacent to shophouses (B) may vary from least to medium-less visibility, least to medium openness, smallest to medium-small scale; the variation depends largely on the width of the adjacent streets. In general, the order of visibility, openness, and scale, from lower to higher is shophouses (B), HDB blocks (A), and finally private towers (C) is the highest. These perceptions apparently are more depended on the geometrical typology of the surrounding buildings, which may not depend only on public-

private nature of the developments. Or we may also conclude that these perceptions are more influenced by urban space and street typology than by residential typology.

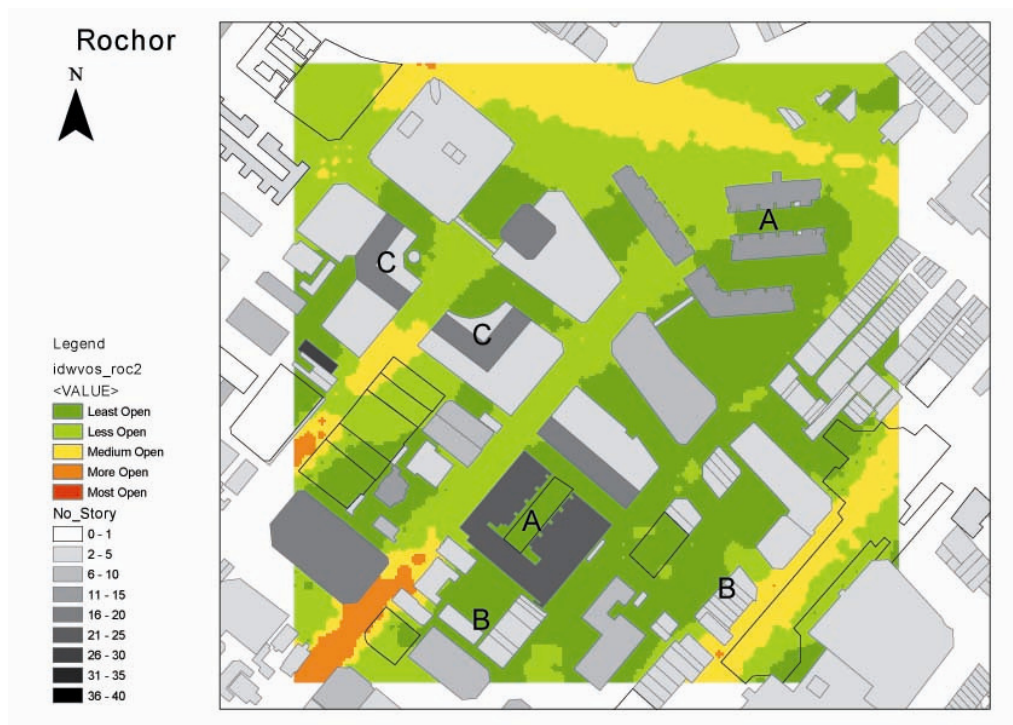


(a)

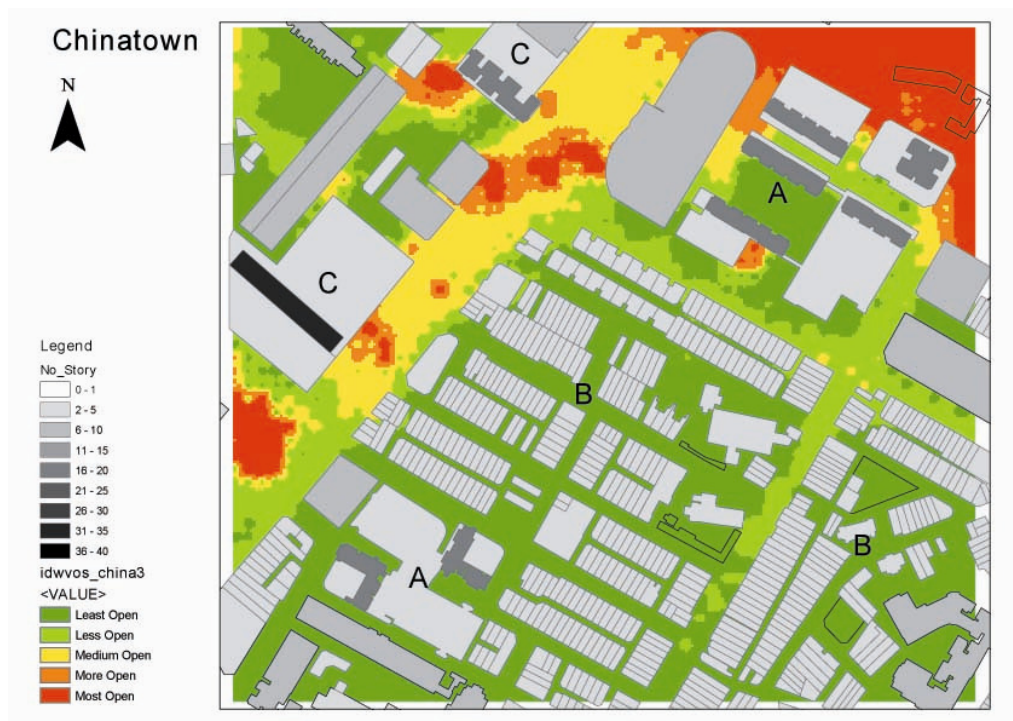


(b)

Figure 16 Visibility mapping at (a) Rochor and (b) Chinatown district residential environment (A: HDB blocks; B: traditional shophouses; C: private apartments and condominiums)



(a)

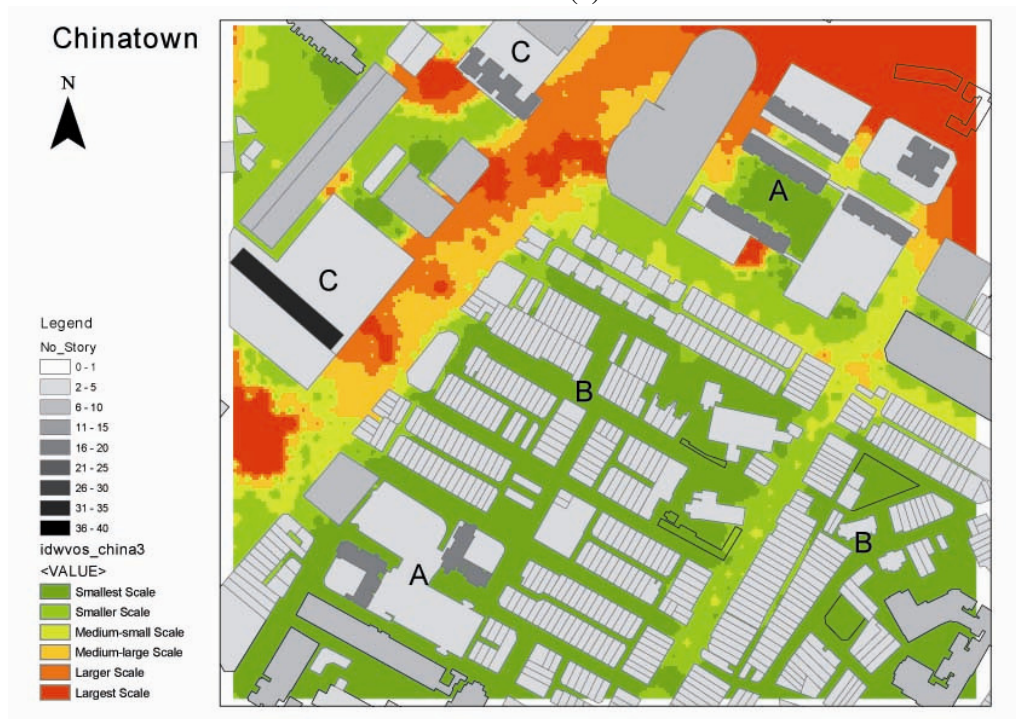


(b)

Figure 17 Openness mapping at (a) Rochor and (b) Chinatown district residential environment (A: HDB blocks; B: traditional shophouses; C: private apartments and condominiums)



(a)



(b)

Figure 18 Perceived scale mapping at (a) Rochor and (b) Chinatown district residential environment (A: HDB blocks; B: traditional shophouses; C: private apartments and condominiums)

However, there are unique characteristics observable for each residential typology. Typical HDB estates (A) have multiple blocks situated nearby, in some cases creating an enclosed space or

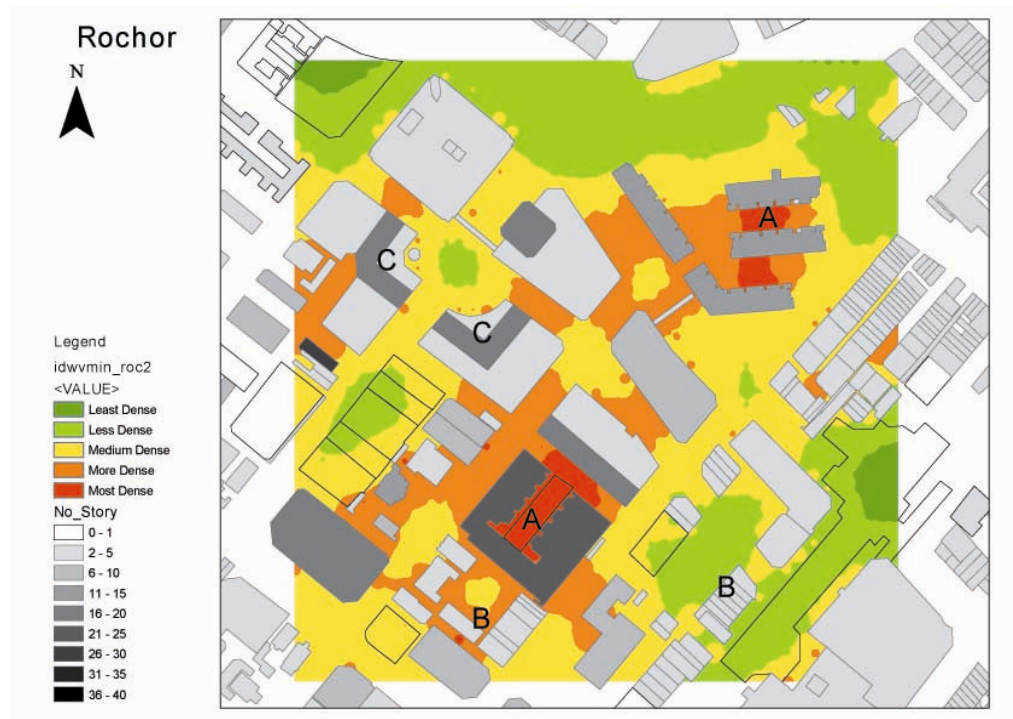
‘plaza’, which has the least visibility, openness, and smallest scale. Shophouses (B) are always situated next to streets, so the streets’ dimension determines the perceptions of their nearby spaces. In traditional setting of Chinatown, shophouses (B) are always clustered closely along a narrow street in the centre of the district, thus they tend to have less visibility and openness, and smaller scale. A private residential tower (C) usually consists of a ‘podium base’ with a ‘tower’ on top, causing higher *VoS* to surrounding spaces. This typology is usually situated next to a wide street or boulevard, thus it tends to have more visibility and openness, and larger scale, especially in the case of Chinatown. The main boulevard along the northwestern side of Chinatown has exceptionally the most visibility and openness, and the largest scale, because it was paraded by high-rise high-density private residential towers (C).

The predictive mappings of environmental perceptions in Figure 19 and Figure 20 reveal their relationships with urban space typologies and with residential typologies. These perceptions of density and daylight are predicted from two corresponding indicator, *VSI* and *SVF*. They can be discussed in relations with urban space typology. Less density and more daylight are perceived along wide boulevards of Rochor and Chinatown districts, while along narrow streets less to medium density and medium to more daylight can be perceived. Medium to more density and less to medium daylight are perceived from spaces adjacent to buildings. More to most dense and least to less daylight are perceived from spaces between nearby buildings. The ranges of these perceptions depend on the height of adjacent buildings and the horizontal enclosure of the space. Higher building surfaces and more enclosed urban space will increase perceived density and decrease daylight of adjacent urban space.

These environmental perceptions can also be discussed in relation with residential typologies. Medium to most density and least to medium daylight are perceived on spaces adjacent to HDB blocks (A). Less to medium density and medium to more daylight are perceivable on spaces adjacent to the traditional shophouses (B). Finally, less to more density and less to more daylight can be perceived from spaces adjacent to private residential towers (C). The typologies can be ordered based on their perceived density, from lower to higher: private residential towers (C), shophouses (B), and the highest are HDB blocks (A). The reverse order can be applied to perception of daylight.

In the same case with spatial perceptions, environmental perceptions apparently are more depended on the geometric typology of the surrounding buildings, which are not depended on public-private nature of the developments. Or we may also conclude that environmental perceptions are more influenced by urban space and street typology than by residential typology. However, we still observed unique characteristics of residential typologies, which affected the perceptions of their nearby spaces. HDB estates (A) are usually arranged encircling an enclosed public space similar to plazas, where most density and least daylight are perceived. Traditional shophouses (B) depends much on adjacent streets’ dimensions, and in the case of Chinatown district, they are clustered closely, and thus perceivable as medium density and medium daylight. Private residential towers (C) in downtown area are usually located next to a boulevard or major transportation nodes and lines, thus less density and more daylight are perceivable from spaces nearby.

In these two districts, the question is what structures the residences perception of their living environment. We may propose that the shape and dimension of boulevards and street networks, and the clustering of similar residential typology, structured the spatial perception of residential environment.



(a)



(b)

Figure 19 Perceived density mapping at (a) Rochor and (b) Chinatown district residential environment (A: HDB blocks; B: traditional shophouses; C: private apartments and condominiums)



(a)



(b)

Figure 20 Daylight mapping at (a) Rochor and (b) Chinatown district residential environment (A: HDB blocks; B: traditional shophouses; C: private apartments and condominiums)

6. Conclusion

Mental geography, in terms of spatial and environmental perceptions of residential environment can be analysed and predicted empirically and spatially, using a GIS-based 3D visibility analysis on 3D model of the environment, namely Viewsphere 3D Analyst, generating volumetric indices such as Volume of Sight *VoS*. We've concluded before that 3D visibility analysis, with its volumetric measure of visible space, is more related to human spatial perceptions than 2D visibility analysis with its planar measure.

A predictive methodology using predictive regression model and perceptual classification of *VoS* is able to generate mapping of spatial and environmental perceptions of residential environment. The methodology has been applied on cases of high-density residential environment in Singapore. Analytical results of these cases and their patterns are also concurrent to the previous study's statistical correlations between Viewsphere Indices (VSIs) and spatial-environmental perceptions (Putra, 2005). The use of classification system is parallel with Lynch's classification system for analysis of urban pattern (Lynch, 1966). The predictive classifications of spatial perceptions are found to be useful for delineating urban spaces based on these perceptual classes. Since spaces delineated were observed to have close relationships with spatial typologies such as street, junction, and plaza, we can identify the general nature of spatial perception for each typology.

The mapping of human spatial and environmental perception is a step closer to the comprehensive understanding of mental geography. Spatial and environmental perceptions may lead to the understanding of subjective sense of 'grand vista' or 'scenic view', through extensive human psychological survey. We may conclude that designing residential environment with deeper understanding and for the benefit of residences' spatial and environmental perceptions preferences, by applying artistic principle of visual order, will improve residences' psychological well-being. We may also conclude that consideration of residence's environmental perceptions of perceived density and daylight will improve their thermal comfort and energy efficiency, depending on the country's climate.

Based on the findings of this study, we may argue that the shape and dimension of a district's urban spaces (streets and plazas) and the buildings' nature of clustering structure the residential district perceptually. In example, clustering of buildings with similar typology will create a profound character of the district. This is concurrent with Lynch's discussions of managing the sense of a region (district) using notable elements to shape the image of the city. Our definition of urban space typology of streets and boulevards, spaces nearby a building, and spaces between buildings, may be correlated with Lynch's elements (Lynch, 1960, 1976).

The question of how public housing programme changed the residences' mental geography of their living environment has been answered partially using this methodology. The older generation of Singaporean who used to live in traditional shophouses in low-rise and super high-density condition will remember the various problems they were facing because of overcrowding. However, there are positive aspects can be perceived in the shophouses area, which are intimacy, vibrancy and vernacular originality. The public housing programme has changed their living environment from low-rise to high-rise high-density environment, which solved most of the problems, while forcing the residences to change their psychological preference and familiarity. The new high-rise environment certainly brings positive impacts to spatial perceptions, such as visibility, openness and scale, inspired by designer's idea of "living the Corbusian dream". However, there are negative impacts as well, because the residences' may not be familiar with living in such high density, as they perceive. This doesn't seem to be a problem in Singapore, since living in high-rise housing estates is the norm today. However, higher density and lower exposure of daylight in mass high-rise public housing environment in different countries, i.e. European and North American countries, may have problems of residences' environmental

psychology, behaviour and thermal comfort. These problems may contribute to the failure of public housing programme in some countries. The question is what is the possible solution? What have Singapore's public housing authority done to solve them? One of the solutions is by improving the design quality of public spaces of HDB estates, creating highly 'greened' and beautifully landscaped in-between spaces, and allowing ground floors to be opened to reduce perceived density. In general, the public housing policy to relocate residences from problematic low-rise shophouses in downtown area to high-rise HDB estates in the fringe bring positive impacts for their spatial perceptions, but less positive impact for their environmental perceptions of density and daylight.

The social stigma is mass public housing programme may be inevitable, since residences still aspire to live in exclusive private developments, following the step of their 'more affluent' neighbours. This trend creates market for private housing developments as an alternative to public housing, which comes with higher price, higher economic status, and for the high-rise ones higher visibility, openness and scale. From this study we've also discovered that such private housings are usually less dense and receive more daylight than HDB blocks, and have easier access from major transportation nodes.

This study was not conducted without limitations. Urban vegetations are not taken into account in the 3D visibility analysis because they can't be modelled in current GIS-based TIN model. In fact the current GIS data structure does not have the capacity to handle true 3D geometry (having more than one z value for an (x,y) location). More sophisticated models such as from Light Detection and Ranging (LIDAR) sensor may be able to accommodate vegetation objects in the future. The 3D model itself is not complete because of difficulties in data collection, such as at the northeastern side of Chinatown model, which may alter the analysis' result. The survey of human spatial perceptions was conducted on a group of 40 samples with similar age (20-22), education (tertiary), and social background. The number of samples was deemed adequate considering the difficulty to assemble adult sample group with uniform social and academic background. The number is close to the number of samples surveyed in Lynch's study (Lynch, 1960). The statistical relationships, regression models, and predicted classifications between respondents' perception and perceptual indices can be refined with more respondents and more locations appended in the study, which is our future endeavours.

Acknowledgment

This research is partially funded by Singapore Millennium Foundation through first author's scholarship scheme.

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