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CAN 3D VISIBILITY CALCULATIONS ALONG A PATH PREDICT THE PERCEIVED DENSITY OF PARTICIPANTS IMMERSED IN A VIRTUAL REALITY ENVIRONMENT?

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ABSTRACT

The wellbeing of pedestrians in an urban setting is central concern in the dense urban context for both current and future cities. A sense of crowdedness may greatly influence the public's physical and mental health. Urban centres attract a large concentration of pedestrians and the perception of crowdedness may affect human comfort and even interfere with activity. Structural 3D morphology and additional elements that make up the visible environment, such as vegetation and exposure to a view of the sky influence perception along a pedestrian path. Walking in the centre of a broad boulevard shaded with trees and surrounded by4-6 story buildings would be perceived differently than walking along a side walk adjacent to very tall buildings. Recently, many intense studies have been examining walkability, wayfinding, human cognition and decision-making along pedestrian paths in the urban environment. At the same time, several spatial modelling and analysis tools have been developed to represent and explain variant phenomenon in this complex environment; amongst them models focusing on 3D visual analysis and its relation to human perception. 3D LOS visibility analysis has been found to be an accurate indicator of perceived density experienced by participants in various studies.

In this paper we will present a dynamic LOS 3D visibility analysis for pedestrian paths examining variant layers of visual information including building structure, streets, trees and the afforded view of the sky. A virtual model of the environment was developed using Grasshopper and Rhinoceros software. The model allows for variations of the same path to be examined with several different parameters such as height of buildings, orientation of path, location of path (middle of boulevard or side walk) and the presence or lack of trees. The dynamic movement of walking an urban path was then represented as the accumulated visibility calculations of the viewpoints along that path directed towards a static target point. Model calculations were assessed by way of an extensive experiment in a visualization lab where participants were immersed in virtual reality environments. Participants were asked to imagine they are walking down a main street in a city, towards the end of the street while on their way somewhere. Participants were asked to record their perception of density for each path. The estimate ranged from 1 (not dense at all) to 7 (very dense). The difference in the evaluations between paths was compared to the variance between visibility calculations in the same respective paths. This 3D visibility model may become an essential tool in the planning and design of public spaces in existing and future cities.

KEYWORDS

3D Visibility Analysis, 3D Isovist, Perceived Density in Public Spaces, Urban Environments, Virtual Environment Experiments.

1. INTRODUCTION

The wellbeing of pedestrians in an urban setting is one of the key issues to be concerned about in dense cities (Salingaros, 2005; Borukhov, 1978). A sense of crowdedness may influence the physical and mental health of the public (Berry, 2007). Urban centres attracts large concentrations of pedestrians and the perception of crowdedness may affect human comfort and even interfere with day to day activity. Visual perception has the power to affect people's thoughts and behaviour as the human environment is largely understood through our vision, and visibility influences the perception of space (Cullen, 1971; Broadbent, 1990; Kultsova et al, 2013; Fisher-Gewirtzman, 2016b). In this paper, we refer to the perception of density formed by the morphology of the 3D environment (topography, built structures and large trees) surrounding the observer. Simulating the visibility of urban pedestrians, while walking along urban paths, allows us to get a good sense of their visual perception of that urban space.

Researchers have endeavoured to describe the complexity of the urban structure as well as the analytical models and tools that attempt to represent this complexity while measuring the wide range of data with its numerous characteristics (Batty, 2013). These efforts try to define quality urban environments that provide sustainable and healthy lifestyles. Some academic research, in addition to contributing to science itself, aims at contributing to actual development and improvement of urban planning and urban design practices. The findings are not always accessible to the practitioners in the form of tools or terminologies. Some studies try to overcome this barrier by collaborating with practitioners (Kultsova et al, 2013) or ensure actual consulting, with strategic, evidence-based consulting services.

In this paper we focus on 3D visibility analysis that simulates the way pedestrians would potentially visualize the urban environment while walking along public pathways. The application of our 3D LOS visibility analysis, which in addition to referencing geometry, also takes into account other basic characteristics of the built environment such as the type of surfaces, buildings, pavement surfaces, trees and the view of the distant sky. The ability to distinguish between the different components of the environment and a person's visibility in relation to them, briefly illustrates the great potential for future use of such comparative analysis. To help bridge academic research with practical design, our current 3D LOS analysis tool was developed with Grasshopper and Rhinoceros software, programs that are largely accessible to most architectural or urban design firms.

1.1 OBJECTIVE

The main objective of this study is to develop a 3D LOS visibility analysis for pedestrian movement in urban spaces (such as pedestrian paths and plazas). The model used is based on previous development of 3D visibility analysis (Fisher-Gewirtzman, 2003; Fisher-Gewirtzman, 2006; Fisher-Gewirtzman, 2016).

In this paper we conduct a comparative analysis of the same public path reconstructed with variations of building heights, with and without large trees, different orientations of movement (centre of the boulevard or on the side walk) as well as directions of movement. Our aim was to study how the variations influence the dynamic 3D visibility calculations, simulating the different perceptions.

The final objective presented in this paper was the assessment of the model. Assessment was based on a comparison of the 3D visibility calculations to the participant's evaluation in a virtual reality laboratory. Such controlled studies have been proven to be a reliable source of information (Mavridou, 2012; Portman et al, 2015; Natapov and Fisher-Gewirtzman, 2016). An extensive study in a visualization lab was conducted, where participants were immersed in virtual reality. Participants were asked to imagine they are walking down a main street in a city, on their way somewhere and were asked to record their perception of density for each path. The estimate ranged from 1 (not dense at all) to 7 (very dense).

The assumptions in this study are that 3D visibility calculations along variant paths can be an indicator on the perception of space, while focusing on the perceived density. Prior work confirmed that measured 3D visibility can help predict the perceived density estimation and show how the increased visibility in a space may be evaluated with a lower perceived density (Fisher-Gewirtzman, 2003; Fisher-Gewirtzman, 2015; Fisher-Gewirtzman, 2016a). In some cases, the view rating (Feitelson, 1992; Lang and Schaffer, 2001), or elements in the view such as trees, can overcome limited visibility and influence the perceived density. A conceptual model combining both the quality and quantity evaluation of the view was presented in Fisher-Gewirtzman (2016b) and Golub et al (2017). One of our main assumptions is that 3D LOS visibility calculations simulating visibility in movement will have a strong relation with the participants' evaluations.

1.2 BACKGROUND

A. URBAN DENSITY AND THE PERCEIVED DENSITY

Dense urban environments have become a central issue in recent years, whose impact will only continue to grow in the future. There is a close relationship between density and environmental attractiveness, and an affinity as well as a dependency of urban density on urban environmental quality (Fisher-Gewirtzman, 2006). The question is how to maintain quality dense urban environments and to avoid the feeling of overcrowding.

Perceived density and crowding are based on the principle that the same density can be perceived and evaluated in very different ways by different people, under different circumstances, in different cultures and countries (Churchman, 1999). The concept of perceived density illustrates how physical phenomena can be manipulated in an attempt to increase the probability of either greater or lesser perceived density (Jacobs and Appleyard, 1987). There are several research projects that have investigated the relationship between urban morphology and its experiential qualities perceived by users (Kultsova et al., 2013), and it has been noted that the density of alternative spatial configurations in the same objective density can be perceived differently (Fisher-Gewirtzman et al, 2003; Shach-Pinsley et al, 2006). In this paper, the significance of experienced density refers to the influence the physical 3D environment has on the perceived density, similar to the definition in Jacobs and Appelyard (1987).

Our variant paths share the same urban plan, but represent different physical densities in regard to building's heights: 4-6 stories in height and extremely tall towers. We refer to the visibility and perceived density of the "corridor" created by the towering walls of the surrounding buildings. The variables of our paths include the height of buildings, the existence of large trees and the orientation of pedestrians' path.

B. THE INFLUENCE OF THE BUILT ENVIRONMENT ON PEDESTRIAN BEHAVIOUR AND PERCEPTION

In recent years, many studies have been examining the influence of the built environment on pedestrian behaviour and perception of space (Zacharias, 2001). The analysis at Handy et al (2007) shows that the built environment has an impact on walking behaviour even after accounting for differing attitudes and preferences. Quality walking environments are one of several broad factors influencing walking behaviour, along with demographic characteristics, attitudes and the presence of desirable destinations (Adkins et al, 2012). Based on prior work we argue that low perceived density will contribute to the quality of the pedestrian friendly environment. Forsyth and Southworth (2008) regard scale as an influencing parameter of pedestrian behaviour. They provide a wide range of definitions for walkable environment, all influenced by physical characteristics. Edwing and Handy (2009) suggest operational definitions for human scale as related to the number and length of lines of sight which corresponds with the 3D LOS Visibility Analysis. They argue that the number of long lines of sight contributes to human scale perception as well as other very specific characteristics such as proportions of street level, building heights and vegetation.

Adkin et al (2012) found that green streets, parks, separation from vehicle traffic and pedestrian network connectivity can significantly contribute to walkability. Aligning trees create more pleasant walking paths (Forsyth and Southworth, 2008) and street trees are considered to have the power to moderate the scale of tall buildings and wide streets (Edwing and Handy, 2009; Arnold, 1993), Trees are an important variable in our case studies.

C. VISUAL ANALYSIS AND SIMULATIONS PREDICTING HUMAN PERCEPTION

Visual perception of space is one of the factors that define spatial experience and cognition of architectural or urban space (Kultsova et al, 2013). Lynch (1960) stressed the importance of view analysis using terms such as 'visual absorption', 'visual corridor' or 'visual intrusion'. Many research studies have explored the relationship between urban space morphology and how users perceive their experiential qualities (Fisher-Gewirtzman, 2017) some in 2D and some in 3D visual analysis.

2D visual analysis is based on Isovist measurements, i.e. the 2D field of view from a specific view point, first introduced by Tandy (1967) in landscape geography. Benedikt (1979) introduced the concept to architecture studies, while various visual analysis and tools have subsequently attempted to predict human perception and behaviour. Weiner and Franz (2005) used Isovist measurements to describe indoor scenes, correlating them with behavioural data. They suggested that Isovist measurements are a promising means to predict the experience of space and spatial behavioural tasks.

Space Syntax (Hillier and Hanson, 1984, Hillier, 1996) is a set of analysis technologies that makes use of graphs consisting of paths and nodes aiming at identifying the variables that define the social meaning and behavioural relevance of spaces. This technique was developed to analyse spatial configurations, from room layout to larger urban scale planning, assuming flat topographical conditions. Turner et al (2001) introduced a visibility graph for the spatial analysis of architectural space, and investigates the relationship between the visual characteristics of a location and their potential social interpretation. Batty (2001; 2004) described how a set of Isovist measurements could form a visual field, whose extent defines other Isovist fields of different geometric properties. He suggested a feasible computational scheme for measuring Isovist fields, and illustrated how these could visualize spatial and statistical properties by using maps and frequency distributions. Isovist computation has mainly been used for analysis at building scale, and 'space syntax' is a suitable technique to quantify environmental and spatial indicators at the urban scale.

Dalton and Dalton (2015) give a recent overview of the 3D visibility analysis and representations of three dimensional isovists. They discuss the various attempts and their ability to represent meaningful complex spatial information and invited expert participants to evaluate these various attempts. Their work followed an earlier contribution to 3D analysis by Pen et al (1997), who developed a flexible 3D virtual environment enabling a range of analytics and design support tools including ISOVIST and AXIAL maps within 3D virtual models.

Morelo and Ratti (2009) argued that traditional calculation methods used are too remote from real human visual experience, mainly because the models do not consider the vertical dimension and the dynamic aspect of visibility, namely, moving through space. In Fisher-Gewirtzman and Natapov, (2014) a comparison between 2D and 3D visibility analysis was conducted on an urban site with substantially significant topographic conditions. Rating the calculation outcomes showed that in level areas, both 2D and 3D had similar results but that in sloped areas 2D visibility analysis, did not or could not capture the true nature of the 3D environment.

Wasim S. (2013) developed an algorithm for 3D Isovist measurements, and demonstrated how this model could be integrated with GIS data to influence visibility measurements. Bahtia et al. (2012) made two major contributions to architectural computational analysis, stating that it demonstrated a consistent, 3D Isovist method. Kultsova et al (2013) argued that most visibility analysis methods were not usable and not technically convenient for practitioners and presented a visibility analysis tool for 3D urban environments, and suggested its possible application in urban design practice. Morelo and Ratti (2009) expanded the concept of Isovist i.e. the visible space from a vantage point in three dimensions, and examined how it could help provide a quantitative basis for Kevin Lynch urban analysis. They argued that their analysis allowed for a more useful interpretation of visibility from a visual perception point of view, because outputs of the analysis are stored in a voxel space. Fisher-Gewirtzman et al, 2013 proposed a similar approach, based on subdividing the virtual urban environment into voxels, which represented a visibility value on a regular grid in 3D space. The model enabled users to compute visibility as a continuous figure with in-between values from fully visible up to fully invisible. The 3D voxel based model was assessed using participants' evaluations to the perceived density.

Subsequently, Fisher-Gewirtzman (2015) developed a LOS 3D visibility analysis tool. This method analysed the sum and segmentation of Lines Of Sight (LOS) at each view point inserted in the virtual built environment. The calculated visibility from each viewpoint is based on the accumulated lengths of lines of sight stemming from each viewpoint representing the visibility from each viewpoint in the direction of observation. The current extension for the LOS 3D method makes it possible to separate various elements in the visible environment, as demonstrated in Fisher-Gewirtzman (2016b). This method was further developed to suit movement along a path and used in the current study that makes a distinction between visibility of buildings and pavements, trees, and the sky in all variant paths.

2. DATASETS AND METHODS

The methodology in this study is made up of three consecutive stages: the first was to develop a 3D visibility analysis model simulating a dynamic experience in an urban setting. The second was to conduct comparative analysis on variations of a possible urban path, where each path demonstrated different parameters that were carefully changed or rearranged. The third and final stage was to assess the model with an experiment conducted in a visualization Lab, where the variant virtual models of the relevant urban path were projected to 75 participants for their evaluations. Following are the descriptions of the first and third stages are explained in details as follows:

2.1 THE 3D VISIBILITY ANALYSIS MODEL SIMULATING A DYNAMIC EXPERIENCE

The purpose of this model is to simulate the visual perception during movement in a built environment i.e. calculate the 3D visibility along a path. The model was based on prior models developed and presented (Fisher-Gewirtzman and Wagner, 2003, Fisher-Gewirtzman et al, 2006; Fisher-Gewirtzman, 2015).

The 3D virtual models were created using Rhinoceros software and calculations were carried out based on code developed in the Grasshopper plugin. Visibility is based on Lines Of Sight from each Viewpoint aimed at a target surface. Calculations sum up the accumulated length of all lines of sight from each viewpoint. The dynamic 3D visibility analysis considers consecutive viewpoints along a path defined by the user. The following steps and images describe the model's features:

Definition of a walking path in the 3D model of the built environment (Rhinoceros), computation to the Grasshopper software as illustrated in figure (1) and creation of a reference point in the walking direction. The user can easily define the maximum length of lines of sight for calculation. Since the model was used as a comparative analysis, the characteristic supporting path length and number of viewpoints were identical: all paths were 800m' in length and 100 viewpoints were evenly spread along all paths.

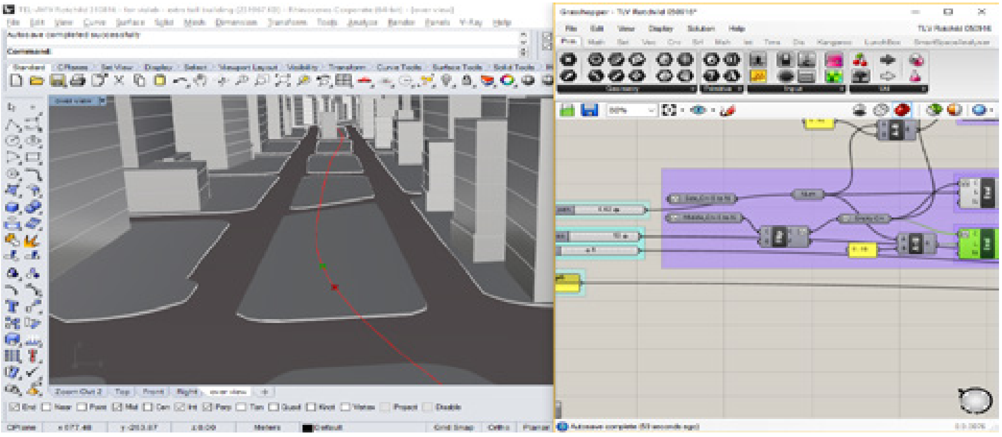


Figure 1 - Defining a walking path in the 3D model

The next step was to create a curved plane representing the 3D field of view, projecting a grid on the plain and drawing lines of sight from the viewpoint, through the grid points towards the surrounding environment as presented in figure (2). The grid points are generated evenly on the curved plain, which represents the field of view in the direction of movement along the defined path. Since a pedestrian can be supposed to have the ability to move his head freely while walking, we referred to a wide potential field of view. The Lines Of Sight (LOS) are intersected by the first opaque element or surface they meet.

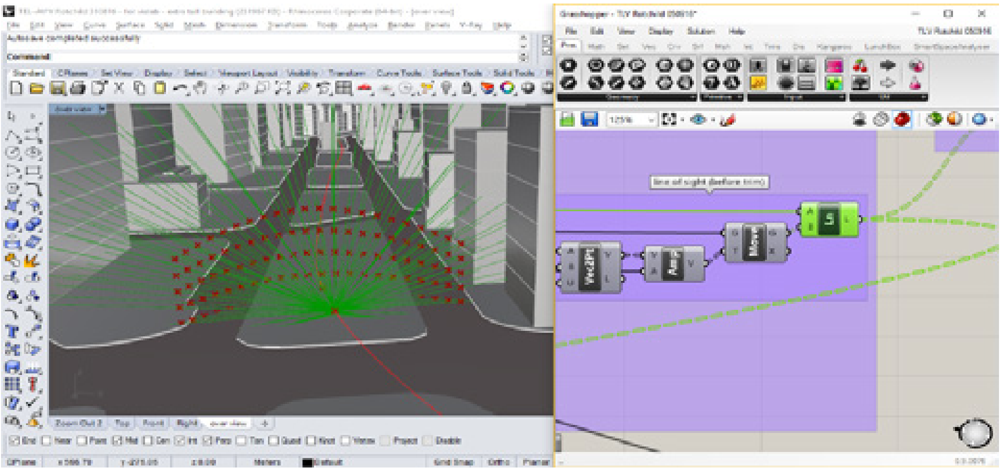


Figure 2 - Defining lines of sight from each viewpoint, through the grid points.

The Lines Of Sight (LOS) are intersected by the first opaque element or surface they meet. The lines of sight can be coloured in accordance to their length as illustrated in figure (3a) (green-long, red-short), or coloured in accordance to the code colour of the layer it reaches (housing, commerce, offices, trees, roads, sky etc.), as illustrated in figure (3b). The colouring by distance represents the LOS distribution and was used to calculate the total visibility for each viewpoint along each path. The colouring by urban function or element was used to calculate separate visibility in accordance to the layer (type of element) the line of sight was intersecting with. This way it was possible to compare how much visibility to building (and building uses) or to trees, water or pavement existed in each path. Additional examples can be found in Fisher-Gewirtzman, 2017a. In this paper, the separate visibility refers to buildings, trees, pavement (street and pedestrian paths) and sky only. The total and separate visibility calculations can be viewed on the right hand-side of table 2.

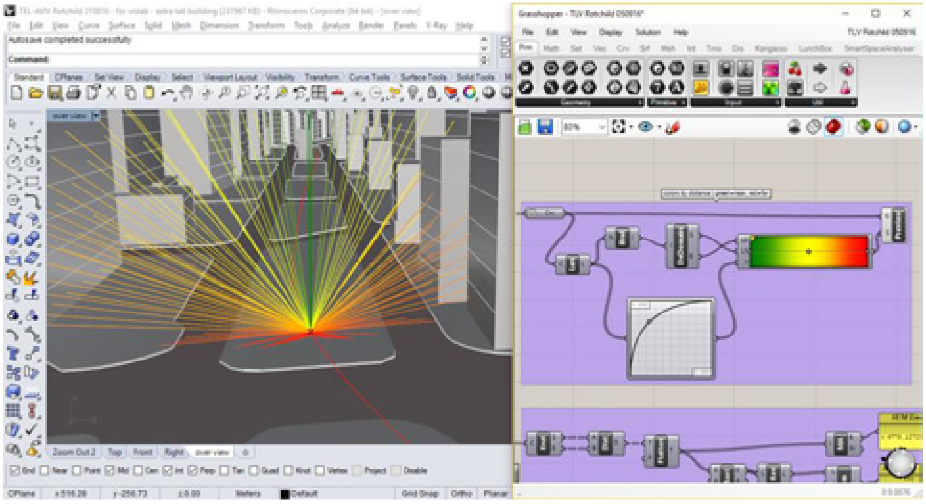


Figure 3a: Lines Of Sight are coloured according to length (red=Short; green=very long)

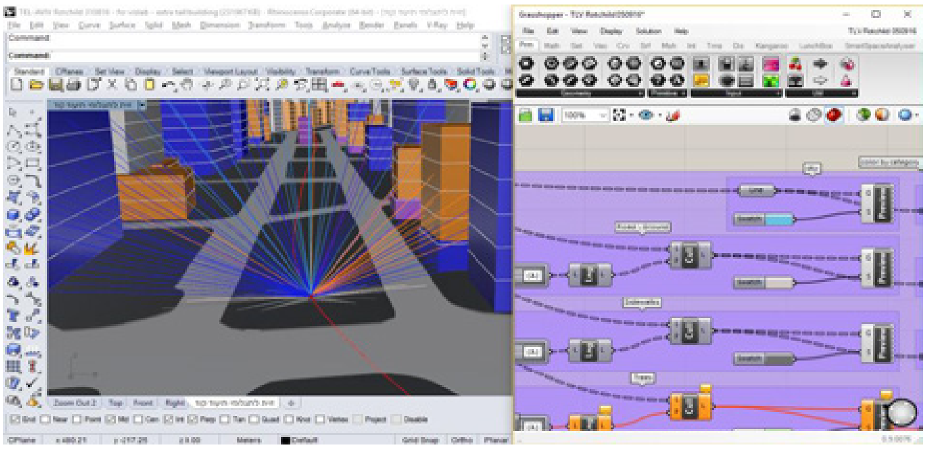


Figure 3b: Lines Of Sight coloured according to the layer (type of element) they intersect.

The final stage consists of summing up the calculations of all viewpoints defined along the path as illustrated in figure (4). The model can provide information regarding the maximum, minimum, average visibility viewpoint along the path, the minimum and average length of LOS (maximum is defined by the user already) visibility distribution to various elements of the environment (defined in layers by the user) etc.

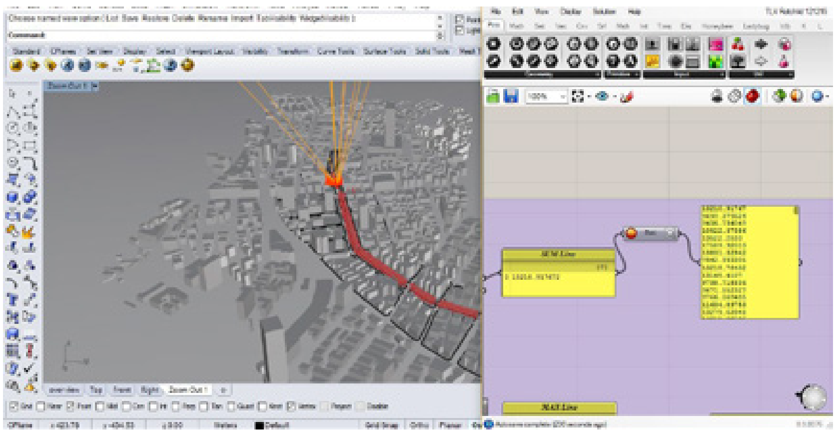


Figure 4: Summing up visibility calculations of all viewpoints defined along the path

The calculation results can be represented by plots that provide a visualization that supports the dynamic characteristics of the simulation and creates a comfortable foundation for comparison.

This model was used to calculate and analyse 3D visibility along variations of the same path. The characteristics of the paths are presented below in table (1). Four longitude sections and perspective views in figure (5) illustrate the variations of the physical environment: existing building heights; existing building heights with trees; additional towers; additional towers with trees. Additional variations are created in accordance to direction of movement and orientation (in the center of the boulevard or walking on the sidewalk. The paths that consist of trees refer to evergreen thick trees that may block visibility. Deciduous trees may bring more variations to the settings of analysis and assessment and are considered for future work.

Group	Path	Contant parameters in groups	variable	variable
A	A-p1 A-p2 A-p3 A-p4	South to North No trees	Center boulevard Side walk Center boulevard Side walk	Existing buildings Towers Towers Existing buildings
B	B-p1 B-p2 B-p3 B-p4	South to North With trees	Side walk Center boulevard Center boulevard Side walk	Towers Towers Existing buildings Existing buildings
C	C-p1 C-p2 C-p3 C-p4	Center boulevard North to South	With trees No trees No trees With trees	Existing buildings Towers Existing buildings Towers
D	D-p1 D-p2 D-p3 D-p4	Towers	North to South South to North South to North North to South	With trees No trees With trees No trees

Table 1 - Group Characteristics

2.2 ASSESSING THE 3D VISIBILITY ANALYSIS MODEL

A controlled experiment was carried out in a visualization lab with 75 recruited participants. The participants varied in profession, in age and in gender. Participants were asked to consider the alternative paths as if they are walking along a central pedestrian street in a city on their way somewhere. They were asked to evaluate their perceived density, ranging from 1 to 7: 1-not dense at all and 7 – very dense. The participants were immersed in virtual reality and exposed systematically to four groups of variant paths. Each group was characterized by some constant characteristics and some variables such as the height of buildings or the existence of trees. The screening order of the paths was shuffled randomly. The paths were presented as short videos, each covering a distance of 80m. Following the experiment, a comparison between the 3D visibility analysis calculation results and the mean value of participant's evaluation for the variant paths presented to them in the lab study was put together for the assessment of the model.

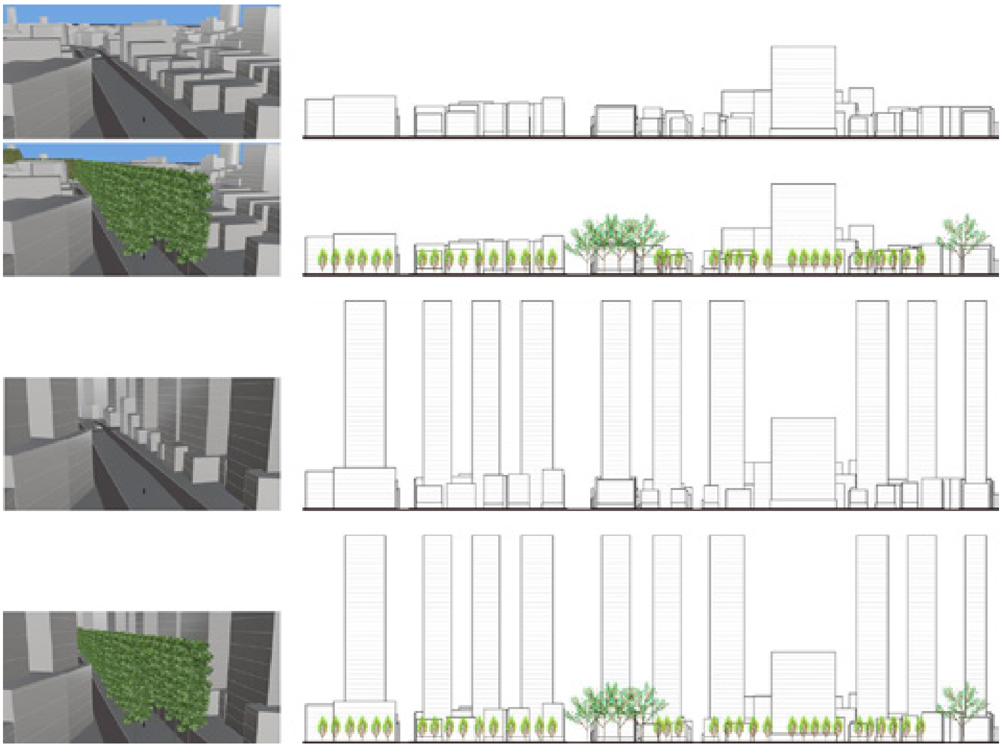


Figure 5: Four longitude sections and perspective views illustrating the variations of the physical environment: (from the top) existing building heights; existing building heights with trees; additional towers; additional towers with trees.

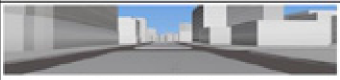
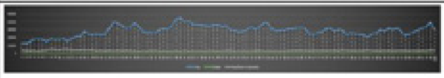
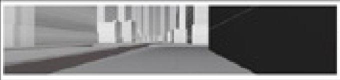
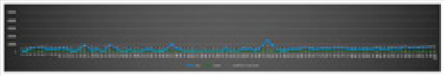
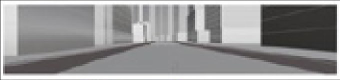
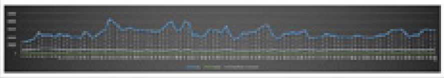
3. RESULTS

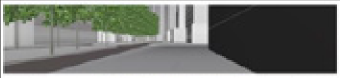
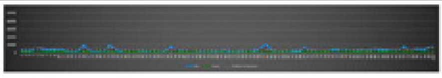
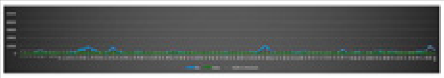
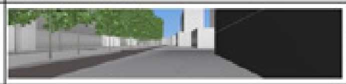
In this paper we present three sub-sections for the results:

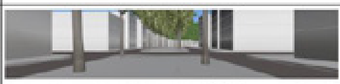
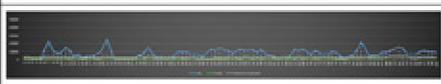
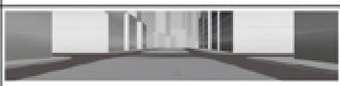
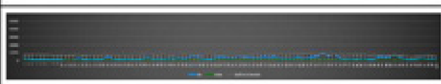
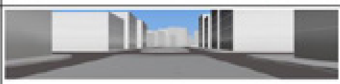
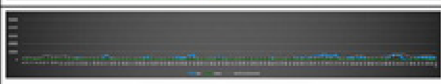
a. The 3D dynamic (4D) visibility analysis results, b. The Visualization Lab study results and c. Model assessment: a comparison between the lab study results and the 3D visibility analysis results.

3.1 3D DYNAMIC VISIBILITY ANALYSIS RESULTS:

The 3D dynamic (4D?) visibility analysis results are presented in four groups, similar to the groups presented to the participants in the visualization laboratory study. Table (2) presents the paths illustrations and plots demonstrating the visibility calculations along each path. Thirteen different paths were distributed between the four groups. Three of the paths are shared by two groups that were screened to the participants. As such, three of the calculations appear twice. Figure 6 is presenting the separate 3D visibility calculations per each path.

Group A						
Path no.	Illustration	Graph	Sum LOS to trees	Sum LOS to built environment	Sum LOS to sky	Total Sum LOS
A1			0.0	388828.8	2861000.0	3249828.8
A2			0.0	661151.2	363000.0	1024151.2
A3			0.0	729385.7	390000.0	1119385.7
A4			0.0	343724.6	2530000.0	2873724.6

Group B						
Path no.	Illustration	Graph	Sum LOS to trees	Sum LOS to built environment	Sum LOS to sky	Total Sum LOS
B1			67416.5	424352.0	289000.0	780768.6
B2			67378.3	332486.8	194000.0	593865.0
B3			67378.3	286524.8	838000.0	1191903.1
B4			67416.5	237886.4	1527000.0	1832302.9

Group C						
Path no.	Illustration	Graph	Sum LOS to trees	Sum LOS to built environment	Sum LOS to sky	Total Sum LOS
C1			60022.9	280163.9	774000.0	1114186.8
C2			0.0	689012.9	288000.0	977012.9
C3			0.0	391783.1	2576000.0	2967783.1
C4			60022.9	330489.8	134000.0	524512.7

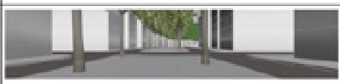
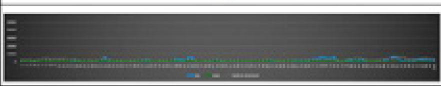
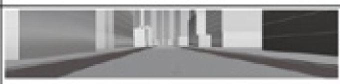
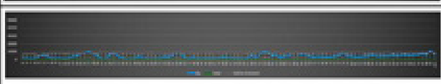
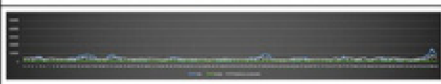
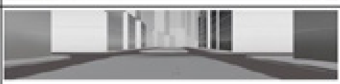
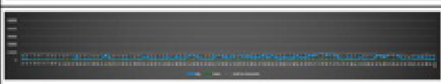
Group D						
Path no.	Illustration	Graph	Sum LOS to trees	Sum LOS to built environment	Sum LOS to sky	Total Sum LOS
D1			60022.9	330489.8	134000.0	524512.7
D2			0.0	729385.7	390000.0	1119385.7
D3			28019.5	134725.1	90000.0	252744.6
D4			0	689012.8642	288000	977012.9

Table 2 - Four groups of variant paths and 3D visibility calculations accompanied by graphs for each path.

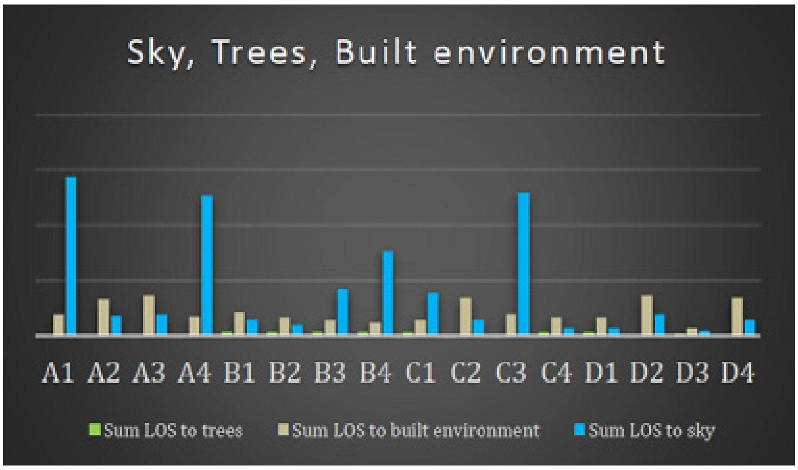


Figure 6 - A representation of the separate 3D visibility calculations per path.

Table (3) shows the ranking of the paths in accordance to their total visibility calculation results. The paths at the top with highest visibility have in common a very open view to the sky. The paths with the lowest visibility at the bottom of the table, all have trees and some are also with very tall buildings that block the openness to the view.

rank	Path no.	Sum LOS Visibility to Trees 10^3m'	Sum LOS Visibility to Built environment 10^3m'	Sum LOS Visibility to Sky 10^3m'	Total 3D Visibility Along the Path 103m'
1	A1	0	388.828	2861	3249.828
2	C3	0	391.783	2576	2967.783
3	A4	0	343.724	2530	2873.724
4	B4	67.461	237.886	1527	1832.302
5	B3	67.378	286.524	838	1191.903
6	A3/D2	0	729.385	390	1119.385
7	C1	60.022	280.163	774	1114.186
8	A2	0	661.151	363	1024.151
9	C2/D4	0	689.612	288	977.612
10	B1	67.416	424.352	289	780.768
11	B2	67.378	332.486	194	593.865
12	C4/D1	60.022	330.489	134	524.512
13	D3	28.019	134.725	90	252.744

Table 3 - Rating of the paths in accordance to their total visibility calculation. Separate calculations are added.

Based on the visibility analysis results we can observe the influence of some of the variables used to manipulate the virtual environments. As an example, let's look at the influence of height by adding towers. Figure (7) presents the total visibility for paths A1 (top) and A3 (below). The only difference between them is the buildings height and as can be expected the visibility is much lower for A3 (with tall buildings). Figure (8) illustrates the separate visibility calculations for the paths. It is observable that the extensive visibility to the sky (blue line) in path A1 is an influencing factor of the visibility calculations.

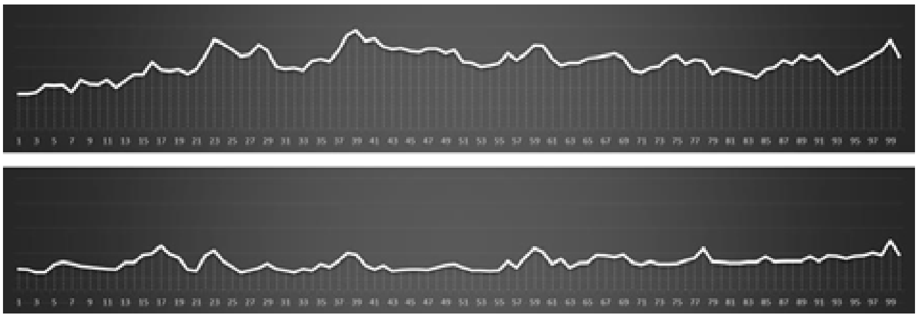


Figure 7 - Total visibility for paths A1 (top graph) and A3 (bottom graph).

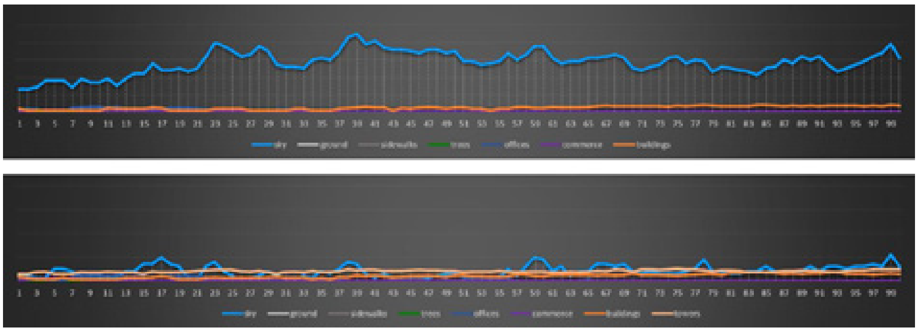
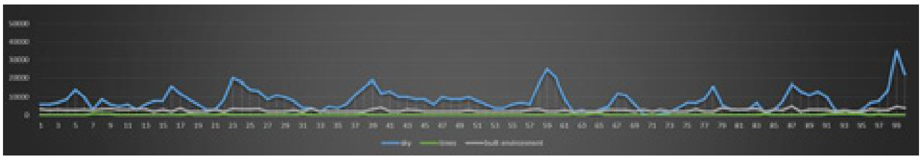


Figure 8 - Separate visibility calculations for paths A1 (top graph) and A3 (bottom graph).

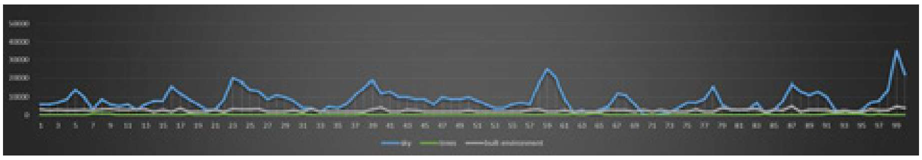
Another possible comparison can be made between the visibility calculations influenced by the presence of trees. Below is the comparison between path A1 and B3. In both paths the movement is along the center of the boulevard in the same direction with low buildings. In A1 there are no trees and B3-with trees. The 3D calculations results are presented in the graphs in figure (9) (A1-top, B3-bottom). Although the green graph in B3 is very moderate, the trees block extensive visibility to the sky view. The straightforward results show that large trees block the view along boulevard. Does it necessarily have a negative influence on perception? We know from prior studies that it may be exactly the opposite (Lang and Schaffer, 2001, Fisher-Gewirtzman, 2016a). Visibility calculations take into account the geometry alone. We can only assume the impact of other elements that make up the view, on perception. This will be examined in a later section that compares visibility calculations with the participant's evaluations.

Figure 9 - Comparison of the 3D visibility results between paths A1 and B3.

Another comparison can be made between D3 and D4. In both paths, the movement is along the centre of the boulevard and with very tall buildings. In D3 there are trees along the centre of the boulevard while in D4 none are present. As can be observed in the graphs in figure (10), the visibility calculations are much lower for D3. Again, this is a result of the trees blocking the visibility to the sky, similar to the comparison between A1 and B3 with the low buildings. Visibility without the trees is almost 4 times higher than with the trees in this comparison.



D-3 3D visibility calculations=252.744*10³m'



D4 3D visibility calculations=977.612*10³m'

Figure 10 - A comparison between the graphs representing the 3D visibility calculations of path D3 and D4.

3.2 VISUALIZATION LAB STUDY RESULTS:

In this paper we present the ranking of the participants' evaluation to their perceived density in a mean value for each of the paths and cross-reference those calculations with the main conclusions from the lab study. Table (4) presents the mean value of the participant's evaluations for all paths in accordance to their groups (A, B, C, and D).

rank	Path no.	Perceived density mean
1	A1	2.28
2	C3	2.65
3	A4	3.04
4	B4	3.21
5	B3	3.25
6	C1	3.60
7	C2	4.05
8	D2	4.20
9	D4	4.29
10	B2	4.40
11	D1	4.41
12	D3	4.43
13	C4	4.48
14	A3	4.53
15	B1	4.56
16	A2	4.99

Table 4 - Ranking of variant paths in accordance to the mean value of the participant's evaluations. (1-not dense at all; 7-very dense)

A1 and C3 are very similar. In both paths movement is taking place in the centre of the boulevard, with no trees and low buildings but they differ in their direction. Therefore, the visibility calculations are both very high and participant's evaluation indicate the lowest perceived density. In a previous study (Fisher-Gewirtzman, 2017) where the results of the virtual reality study in the visualization lab were carefully analysed, various insights stand out:

Regarding the presence of trees: While walking in the centre of the boulevard with existing buildings, the trees increased the perception of density significantly (as seen in path B-3) but while walking on the sidewalk with additional tall buildings, the trees significantly decreased the perception of density (like in B-1). Regarding orientation: Paths without trees were perceived as much denser while walking on the sidewalk and significantly less dense while walking in the centre of the boulevard.

Regarding height of buildings: Tall buildings increased the perception of density significantly, but to a different degree depending on the presence of trees (perceived as less dense) and the direction of movement. In the next section we will look for the relation between the 3D visibility calculations and the participant's evaluations.

3.3 ASSESSMENT RESULTS:

The assessment of the 3D dynamic visibility model was based on several comparisons between the results of both stages. All paths were ranked in accordance to both total visibility calculations and mean value of the participant's evaluations. In table (5) both assessments appear side by side. It is interesting to note that the first five paths are ranked identically in both. The paths with the largest extent of visibility were ranked with the lowest perceived density by participants and in the same descending order. This confirms the strong correlation between visibility and perceived density in the case of high visibility. Additionally, several paths were ranked with a recognizable similarity by both: C1 was ranked 8th by 3D visibility calculations and 6th by the overall participants' evaluation. D4 was ranked 10/11 by 3D visibility calculations and 9th by the

Rank (visibility calculations)	Path no.	Total 3D Visibility Along the path $10^3m'$	Rank (participants Evaluations)	Path no.	Perceived density Mean value
1	A1	3249.828	1	A1	2.28
2	C3	2967.783	2	C3	2.65
3	A4	2873.724	3	A4	3.04
4	B4	1832.302	4	B4	3.21
5	B3	1191.903	5	B3	3.25
6/7	A3/D2	1119.385	6	C1	3.60
			7	C2	4.05
8	C1	1114.186	8	D2	4.20
9	A2	1024.151	9	D4	4.29
10/11	C2/D4	977.612	10	B2	4.40
			11	D1	4.41
12	B1	780.768	12	D3	4.43
13	B2	593.865	13	C4	4.48
14/15	C4/D1	524.512	14	A3	4.53
			15	B1	4.56
16	D3	252.744	16	A2	4.99

Table 5 - ranking the 3D visibility calculations and overall value of participant's evaluations

overall participant's evaluation. C4 was ranked 14/15 by 3D visibility calculations and 13th by the overall participant's evaluation. In some cases we found pronounced differences in the ranking: A3 was ranked as 6/7 by 3D visibility calculations and was ranked as 14th based on participants evaluations. A2 was ranked as 9th according to 3d visibility calculations but was ranked as 16th and most dense according to participants evaluations. D3 was ranked as 16th, the lowest 3D visibility calculations but 12th by participant's evaluations (as less dense). In the case of low visibility calculations, we noticed that the visible elements and their influence on perception is very noticeable, especially in the case of large trees.

Below, we will examine the paths with the greater differences in ranking that occurred in our comparative evaluation between the 3D visibility calculations and the participant's evaluations:

A3 - A path with extra tall buildings, no trees and walking in the centre of the boulevard. This path was ranked as 6/7 according to the 3D visibility calculations and 14th by participant's evaluations, meaning they perceived this path as very dense. The orientation in the centre of the boulevard afforded good exposure to the sky which in turn led to relatively high visibility calculations even with the presence of tall buildings. At the same time, the geometry probably greatly influenced the perception of the participants. The overwhelming sight of so many tall buildings closing on the person walking in between them may be the reason for the pronounced differences in ranking.

A2 – this path was constructed with extra tall buildings, no trees and allowed for walking along one of the sidewalks. Walking along a sidewalk decreases visibility dramatically and therefore it is not surprising that the 3D visibility calculations are lower than the calculations of path A3 as mentioned above. This rating as the densest path (ranked by participants as 16th) can have two explanations. The first explanation stems from the movement orientation. Walking along the side walk right up next to towering buildings may have greatly decreased visibility but also overwhelmed the participants. The second possible reason may be a technical one. Path A2 was part of a group where all paths had no trees and A2 always appeared right after A1 which was constructed with low buildings and was allowed for walking in the centre of the boulevard. The difference between the two may have been perceived as extreme in this group.

D3 – The entire D group consisted of paths with very tall buildings. The variables include direction, orientation and existence of trees. Movement orientation in path D3 allowed for walking in the centre of the boulevard with trees. Due to the tall buildings and the trees, the visibility calculations are the lowest out of all the paths and it was ranked 16th. On the other hand, according to participant's evaluations it was ranked as 12th. The reason for the divergence no doubt, can be explained by the natural preference for trees along urban paths.

4. CONCLUSIONS

In this study, we developed a 3D visibility analysis described as a dynamic visibility analysis (or 4D visibility analysis) that simulates movement along urban paths. To assess the model we conducted a study that explored the effect of various factors that influenced the perceived density of participants in virtual motion as they walked along variations of a pedestrian path. The same variations were used for the 3D visibility analysis and the comparative ranking of the variant paths. The variations focused on the built elements of the environment including buildings, roads and surfaces, large trees, and the sky. A full correlation was found between the rankings of the 5 paths with the highest visibility calculations where participant's evaluations for the paths perceived then as having a low density. Many of the rest of the paths were very closely rated, and only a few isolated paths received different ratings in both categories. The later, can be explained either based on the experiment or by participants' preferences, such as the preference for large trees along the urban path. Large trees would generally block the afforded view (and this is shown to have a great impact on the visibility calculations), but at the same time, create attractive scenery and contribute to the positive evaluations. Such a model that combines quantitative and qualitative analysis, visibility calculations as well as human preferences would be a stronger predicting tool, as suggested in Fisher-Gewirtzman, (2016).

With the further development of the 4D visibility analysis it may become a tool for the practical use of city planners and designers. This tool has the potential for helping predict the influence of changes being considered in existing urban spaces as well as new projects in developing areas. This study is a contribution to the research and development of future cities and the improvement of public spaces and paths in existing ones for the benefit of pedestrians.

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