Topological configuration in wayfinding and spatial cognition: a study with real and virtual buildings for design relevance

Saif Haq, **Glenn Hill** and **Adetania Pramanik**

College of Architecture, Texas Tech University, Lubbock, TX 79409-2091

ABSTRACT: This paper is concerned with the role of topological configuration of building layouts in wayfinding and spatial cognition and with associated design strategies. Topological configuration is the structural hierarchy of *individual spaces* in a layout that arises due to the topological relationship of each space with all other spaces in the layout. This can be objectively measured by Space Syntax theories and methods. The paper discusses the beginnings of the concept and traces its development in cognition literature. It then describes a series of experiments done in three real hospital buildings and in a copy of one hospital that was produced in a virtual immersive reality (VIR). Those studies were reported individually in previous publications. In this paper a comparative analysis is presented which suggests that (1) wayfinding behavior is very similar in real and simple virtual settings, (2) topological properties of layouts as determined by Space Syntax analysis are important predictors of wayfinding use of spaces and (3) Euclidian and metric properties in spatial cognition do not develop easily in simple VIR's, but they do not hamper wayfinding. The first has implications in using computer models for data collection. The second is important for architects because investigations of topological configuration may suggest design moves to achieve wayfinding friendly plans. The third is important to cognition and wayfinding researchers as it brings attention to the relationship between topological configuration and wayfinding success. Implications of the results in light of the design professionals are also included.

Conference Theme: New methodologies in architectural research
Keywords: Plan Analysis, Design Evaluation, Wayfinding, Spatial Cognition, Space Syntax

1 INTRODUCTION

Spatial configuration is generally understood as the arrangement of unit spaces in a layout. Such arrangements can be studied by taking into account *relationships* between spaces. Consideration of Euclidian relationships lead to Euclidian configuration, and its cognition is usually understood as mental maps having both distance and direction knowledge (Devlin, 2001; Golledge, 2003; Piaget & Inhelder, 1967; Siegel & White, 1975). In contrast, considerations of direct and indirect connections between spaces lead to topological configuration (Kuipers, 1983; Remolina & Kuipers, 2004). Since the classic work of Piaget & Inhelder (1967) topological properties of spaces have been considered important in cognition studies. However, methodological advances to *objectively quantify* spatial properties based on topological relationships are a more recent phenomenon. Attempts by Best (1970), Braaksma & Cook (1980), Kuipers (1983), O'Neill (1991, 1992), Rovine & Weisman (1989) etc. are noteworthy in this regard, but their efforts resulted in a *single value for an entire layout* and values for *individual constituent spaces* could not be calculated. In contrast, Space Syntax quantifies unit values for *each space* based on its direct connections to immediately adjacent spaces, secondary connections to spaces one 'step' removed, tertiary connections to spaces two 'steps' removed and so on, until all the spaces in the layout has been considered and the values 'normalized' by comparing with a standard layout (Hillier, 1993, 1996, 1999; Hillier & Hanson, 1984; Hillier, Penn, J. Hanson, & Xu, 1993).

This paper investigates the association between topological configurational values of unit spaces as obtained through Space Syntax analysis of building plans with experimental data of wayfinding and spatial cognition. The experiments were carried out in three real hospital buildings and comparable virtual immersive reality (VIR) model of one of them. The analyses suggest that (1) wayfinding behavior is very similar in real and simple virtual settings, (2) topological properties of layouts as determined by Space Syntax analysis are important predictors of wayfinding use of spaces and (3) Euclidian and metric properties in spatial cognition do not develop easily in simple VIR's, but they do not hamper wayfinding. Among them, the second one has relevance for architects and is highlighted at the end of this paper.

2 BACKGROUND

Environmental cognition is concerned about the way we acquire, store, organize, and recall information about the environment (Gifford, 2002). A subset of environmental cognition is spatial cognition. Spatial cognition helps us wayfind, estimate distances and directions, recognize route cues, make and read maps, and generally understand the relative location of different places (Gifford, 2002). It is an important prerequisite to wayfinding, and conversely, wayfinding can be taken as an indicator of spatial cognition (Golledge, 2003). Spatial cognition research have generally concentrated on three themes: (a) understanding the relationships between the form of the physical world and mental representations, (b) linking space to action and (c) creating alternate methods and approaches for studying environmental cognition (Zimring & Dalton, 2003). This project is concerned with the first. Specifically, it seeks to investigate the association between *relational properties of physical space* with wayfinding and cognition.

Research into the cognitive aspects of the relational properties of space perhaps began with Piaget & Inhelder (1967). From their study about spatial learning in children, they had suggested that *cognitively* important relationships between spaces are topological; projective and Euclidean, and that ontogenetically, understanding of topological relations precedes projective and Euclidian ones. Unfortunately these authors did not have a favorable attitude regarding topological relationships and had also suggested that "…it is impossible for relationships of this type to lead to comprehensive systems linking different figures together by means of perspective or axial coordinates, and for this reason, they are bound to remain *psychologically primitive*" (p. 153, author's italics). The relational characteristics of spatial knowledge was later addressed by Siegel & White (1975), through their concept of 'configuration'. They used the term in the cognitive sense to describe what they called 'a sophisticated wrinkle that gives its owner an advantage in … organizing experience" (pp. 24). In this case, the authors seemed to have had some difficulty in describing this integration of spatial representations, and in the process, perhaps unwittingly set up a perplexity between topological configuration and survey/Euclidian configuration; one that has remained unqualified in subsequent literature. For these authors, configurational knowledge is that which comes from 'landmarks-connected-by-routes" (p. 24) and "…when the routes become interrelated into a network like assembly … becomes configurational" (p. 30). They also discussed varying degrees of integration or gestaltness of that spatial representation (p. 24). Configurational knowledge contains "… a perceived outline of a terrain (e.g. the outline of a United States map); a graphic skeleton … and a figurative metaphor (e.g. the 'boot' of Italy)". Unfortunately, being unable to be more specific, they moved on to describe 'sketch mapping' experiments done by other researchers and their categorization of those as route maps and survey maps (Appleyard, 1970; Shemyakin, 1959). With this, they arrived at the concept of cognitive survey maps and described them as "… coordinations of routes within an objective frame of reference. That is, survey maps become possible only after routes and an objective frame of reference exist" (Siegel & White, 1975:43).

But, what is this objective frame of reference? To many authors, this is Euclidian; and they generally agree that spatial cognition are spatially dominant, metrically scaled and interrelated into a global allocentric reference systems (Hirtle & Hudson, 1991; Montello, 1998).

Another group of researchers have suggested that such a frame of reference can also be topological. For example, Kuipers (1983) said that knowledge of topological relations is distinct from metric relations and that travel is possible without metric knowledge, but not without topological knowledge. Freundschuh (1991) is of the opinion that 'topological configuration begins early and develops into 'topology+metrics' configuration. Topological relationships are non-metric and are maintained under elastic distortions (Newcombe, 1989). Some properties associated with space are proximity, order, separation & connectivity, and continuity & containment (Piaget & Inhelder, 1967).

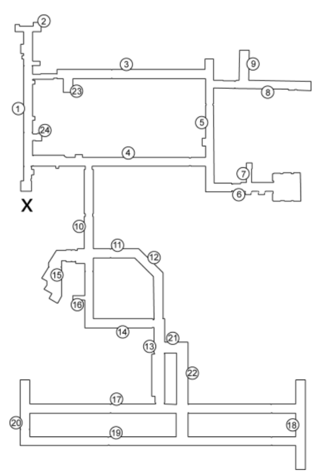

Figure 1: Corridor plan of City Hospital

At this point a common sense description of a person immersed in a large scale environment is described. Note that this description only includes the notions of continuity & containment. Consider the corridor plan of 'City' hospital in figure 1, whose entrance is at point X. As a person enters through the door s/he will get an overview or 'containment' of corridor 1 and, because a spatial system is continuous, a sense of 'connectivity' to other corridors; for example to corridors 2, 3, 4 and 24. If s/he turns to corridor 4, connectivity to 10, 5 and 1 will be available, and from corridor 10 connectivity to 4, 11, 14 and 16; and so on. Every change in direction will make connectivites to different corridors available. Since topology is not about metrics or geometry, the spatial relations described above can be indicated by a system of nodes and connections as in figure 2 a, b, and c for corridor numbers 1, 4 and 10 respectively. Now, since the subject is moving, s/he will reach corridors from more than one entry points, and will bring along knowledge of connections developed in previous corridors visited (spatial cognition). Thus, instead of a simple set of direct connections, a set of secondary, tertiary and sequentially deeper connections will also be understood. This is cognition of spatial 'ordering' and are shown in figure 3 a and b for corridors 1 and 10 respectively. Now, if the focus is shifted from the person to the environment, then the same information can be described in a different manner. For example, corridor # 10 is directly connected to corridors 4, 11, 14, and 16; has a secondary connection to corridors 1, 5, 12, 13, and 15, a tertiary connection to corridors 2, 3, 8, 16, 17, 21, and 24, and so on (see figure 3b). In comparison, corridor 1 has a different topological relationship to all other corridors in the hospital building (compare figures 3a and 3b). Similarly, all corridors are connected to all others through varying degrees of connections. Analysis of plan drawings from this point of view can provide a sense of hierarchy of corridors that is based on its topological relationship to all others. This is topological configuration. To make a distinction, while layout is the overview of spaces with scale and geometry, topological configuration is the structural hierarchy that arises due to their connections with one another.

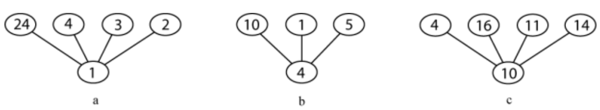

Figure 3: topological relationships to adjacent corridors from (a) corridor 1, (b) corridor 4, and (c) corridor 10

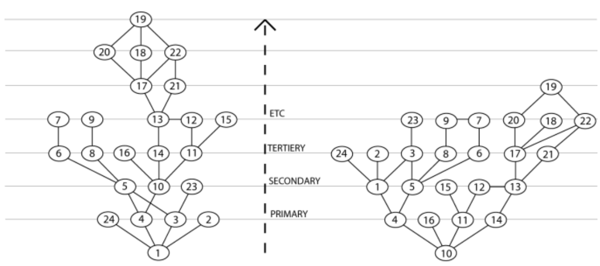

Figure 4: Justified graphs (Hillier & Hanson, 1984) showing topological relationships to ALL corridors from (a) corridor 1, and (b) corridor 10

At this point two things need emphasis: (1) despite Piagian reservations, topological connections can be the frame of reference for configurational knowledge and (2) Space Syntax is the tool to measure topological configuration.

Space Syntax recognizes unit spaces (corridors in our example) and quantifies their topological relations with all other spaces in the layout (Hillier, 1996; Hillier & Hanson, 1984). This topological relationship of each corridor to all other corridors is described through a mathematical concept called 'integration'. A corridor with high integration is, on an average, closely *connected to all other corridors* in a given layout. Conversely, a corridor that is *distant from all other corridors*, on an average, is called 'segregated'. There are also intermediate levels of analysis. For example, integration-3 considers the relationship that each corridor has with only those that are connected *through two intervening corridors*. Space Syntax researchers have also developed various software to calculate integration. An analysis of City hospital using Spatialist (Peponis, Wineman, Rashid, Bafna, & Kim, 1998) is shown in figure 4. In the image, the corridors are shaded such that higher integration-3 values are shown by the darker shade and vice versa. It should also be mentioned that Syntax analysis provides numerical values for each space of a given layout. In this way, architectural plans can be explored with statistical tools. Now, the interesting question to be posed is this: what role do topological configurational values (integration and integration-3) play in spatial cognition and wayfinding? The research is described next.

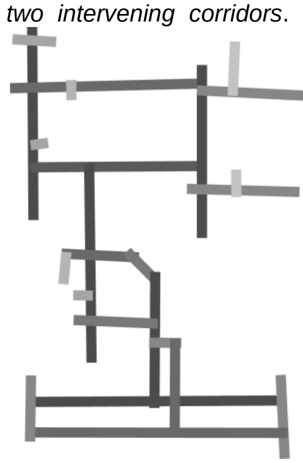

Figure 2: Space Syntax analysis of City Hospital

3 RESEARCH DESIGN

This research included two phases. The first was carried out in three real hospital buildings named Urban, University and City hospitals. The entire floor accessible from the main entrance was used. It included public areas, inpatient zones, outpatient clinics, and administrative sections. However, corridors that had a 'Do Not Enter' sign were omitted. A total of 128 subjects (32, 29 and 67 for the three hospitals respectively), 62 males and 66 females, having a mean age of 19.5 years participated. None of the participants had been in the hospital where the experiment was done, nor had they visited any hospital in the previous six months. After completing a self-report survey regarding their wayfinding strategies (Lawton, 1996), the subjects explored one floor of the hospital for 15 minutes (exploration). Then they were asked to sequentially wayfind four pre-selected destinations. These were chosen so that they were located in integrated and segregated corridors; some had directional signage from other areas and some had none. The tasks were counter balanced so that each location was used both as an origin and a destination for wayfinding. As participants reached each destination, they were faced west and asked to point to previously visited but unseen areas. This was performed by using a circular cardboard with angles marked on it in 10 degree intervals and a pointer attached to the center. Finally the participants drew a sketch map of the hospital floor focusing on the corridors and locations on a 8 ½ by 11 inch paper. Pointing and sketch mapping was done in City and University hospital. The corridors traversed by each subject were mapped on a plan drawing by the researcher who followed along, and from these exploration maps 'total use of corridors' (TUC) data was compiled. From wayfinding maps, 'total use of redundant corridors' (TURC) was gathered. Redundant use was counted when a corridor was used even though it was not in the topologically shortest path between an origin and a destination. TUC and TURC were taken as a measure of exploration and wayfinding difficulty. From sketch maps, drawn corridors were added to get 'appearance of corridors' data. To make sure that the occurrences of corridors in the maps were correctly accounted for, two independent raters in each hospital judged a sample of the sketch maps. The researcher judged all of them. In University Hospital two raters and the experimenter rated 10 maps; i.e. each rater had to judge 320 corridors. They agreed 239 times, or 74.69% (Cohens Kappa=.4937). Average agreement per map was 23.9 times (out of 32) -- maximum 31 and minimum 15. In City Hospital, two raters and the experimenter judged 25 maps that included 600 corridors. Here they agreed 499 times or 83.16% (Cohens Kappa=.6633). From pointing tasks, the deviation in degrees from actual position, called 'pointing errors' were complied. The correlations of corridor use in both exploration and wayfinding with their topological configurational values were high and statistically significant at p=<.05. See table 1. Earlier, Peponis et al (1990) and Willham (1992) had also found high correlations between wayfinding use of corridors and integration values in experiments carried out in a geriatric hospital using both young and old volunteers.

	Relates to topological configuration				Relates to Euclidian configuration	
		Correlation (r values) of Integration-3 and various experimental data (p=<.05)			Average Values	
HOSPITAL	**SUBJECTS**	**TUC**	**TURC**	**CORRIDORS IN SKETCH MAPS**	**POINTING ERRORS**	**SKETCH MAP ACCURACY**
Urban	32	.805	.636			
University	29	.829	.743	.561		
City	67	.775 (60%)	.657 (43%)	.697	39.52	57.92
City Virtual	32	.702 (49%)	.692 (48%)	.823	56.03	37.5

Table 1: Comparison of results in the different hospitals

Regarding spatial cognition, corridors with higher integration values were also featured in more sketch maps. The correlation of corridors appearing in sketch maps and integration-3 values were also high (table 1) A similar work done in an urban area by Kim & Penn (2004) demonstrated that integration-3 values were also correlated to sketch map variables at r=.728.

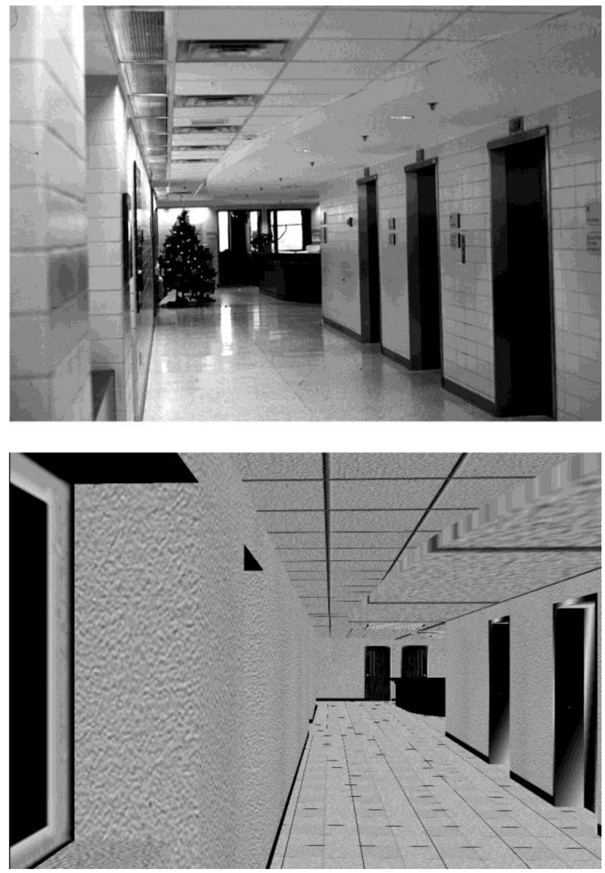

Figure 5: Comparison of real and virtual environments in City Hospital

From these results it was argued that (1) topological values can be used to describe configuration, (2) spaces described from such analysis are predictors of exploration and wayfinding and that (3) they have a cognitive presence. The fact that very similar results were found in very different layouts (in both building interiors and outdoor urban areas) provides credence to such a claim. Unfortunately, one valid criticism remained. The experiments were all done in real settings and there were no 'control' of extraneous environmental variables. As such, the extent of the role of topological configuration remained unclear. To examine this variable, another experiment was devised in a *virtual immersive reality* (VIR) using only the plan and dimensions of City hospital. This VIR model was built from very simple geometries (rectangular shapes). *Here all environmental factors were controlled*. For example, all the corridors had the same floor finish, same wall surfaces, same ceilings and the same ambient lighting conditions. Obviously there were no people to overhear or follow, and certainly no smells (see figure 5). Invisible boxes providing collision detection were inserted so that the users could not 'walk through' the virtual walls. A joystick was selected as the user input interface. Witmer & Kline (1998) had commented earlier that the VIR user has the ability to relate the movement of the joystick with the movement in the virtual world (e.g. pushing the joystick forward means the user move forward). The joystick was calibrated not to go faster than the speed of a walking person. Before conducting the experiment, a pilot study was undertaken with 12 subjects and various configurations of hardware.

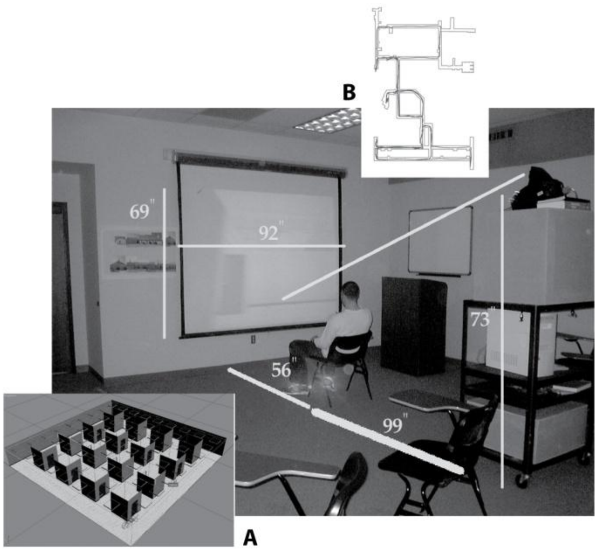

Figure 6: Experimental setting

The experiment consisted of six phases. In the beginning, the participants filled out a self report questionnaire about their wayfinding strategies. (Lawton 1996). The second phase was pre-training, i.e. getting comfortable using the joystick and navigating within a generic VIR environment for 5 minutes. For this purpose, a 72 feet by 72 feet virtual environment was developed containing 10 corridors (5 x 5) arranged in a grid pattern (see figure 6 inset A). The third phase was similar to the open exploration done in the real hospital. The users were taken to the entry door (same location as in the real building) and were asked to navigate within the model for a maximum of 15 minutes. At this time, they were also asked to pay attention to four colored doors (red, green, blue and magenta) that corresponded to the four locations used as destinations in the real building. After completion of open exploration, each subject was asked to perform wayfinding searches similar to that done in the real environment (fourth phase). A new VIR file was opened which positioned the user in any one of the four colored doors and then was asked to 'walk' to another colored door. Like the experiment in the real building, they were given a maximum of 10 minutes. If, after that time, the destination was not found, the researcher would stop the experiment and escort the user to that destination. There, another VIR file was opened which put the user in the same location. S/he was turned to face west and asked to point to the location that s/he had come from and those that s/he had visited before (fifth phase). This procedure was repeated four times until the user had walked to all four colored doors. Finally, (sixth phase) the user was asked to sketch the hospital corridors as s/he remembered it on a 8½ by 11 white sheet of paper.

A computer tracking module was developed to report positions of the participant in the VIR. The x and y position data was transferred into AutoCAD software as lines which illustrated the paths each participant completed (figure 6, inset B).

Data was collected from 32 undergraduate students (9 males and 23 females). Two persons could not complete the experiment. This was mainly caused by motion sickness. However, based on Stanney (1998), the two that dropped out (6%) was not unexpected. Twelve of the subjects never had previous experience of using a joystick. Nevertheless, they could all complete the experiment.

Exploratory behavior was characterized, as before, by the 'use of corridors' (TUC) and wayfinding behavior by the '*redundant* use of corridors' (TURC). 'Pointing accuracy' was also calculated in the same manner as in the real hospital. However, sketch map analysis was done in two ways. First, 'appearance of corridors' was done as before. Additionally, a second variable, 'sketch map accuracy' was compiled. Since this was not done in the maps drawn from the real building, both sets of sketch maps were analyzed. This was calculated by an independent rater not familiar with the building. First, the hospital was considered as three sections (the layout of the hospital 'afforded' this. Refer to figure 1). Each map was looked at by sections and then as a whole. After comparing with an actual plan, a grade from 0 to 25 was given to each section. A deduction of 5% was made for each error in each section of the map. The maps were also judged as a whole (0-25) and 5% was deducted for errors in direction or connection of each section in relation to the whole. The same rater also rated the sketch maps in both the real environment and the VIR experiment. It would have been preferable to have more raters evaluating these maps, but time and costs prevented this. However, there can be some confidence that maps from the two experiments were rated by the same person. A final set of data collected was 'percentage of wayfinding successes'. At this point, one distinction needs emphasis. TUC, TURC and corridors in sketch maps were analyzed from the point of view of topological configuration. Pointing errors and sketch map accuracy were indicators of Euclidian properties in spatial cognition.

4 DATA ANALYSIS AND DISCUSSION

Data from the virtual and the real environments was compared through two-sample t-tests assuming unequal variances (see table 2). Since the p-values are much less than 0.05 in all the cases, it seems that there is a substantial difference between the two datasets. On the other hand, the average use of corridors in open exploration in both the environments demonstrated a similar pattern (see figure 7). The average wayfinding success was 79% in the real environment and 76% in the VIR with variations in the individual searches (see figure 8).

		t values	P values (one tail)	Relates to
Open Exploration	TUC	1.889	0.0332	Topological Configuration
Directed Search	TURC	2.866	0.0035	
Cognitive Tests	Appears in Sketch Maps	5.957	<.0001	
	Pointing accuracy	-2.503	0.0079	Euclidian Configuration
	Sketch Map Accuracy	3.402	.0006	

Table 2: Results of two-sample t-tests (assuming unequal variances) showing the relationship between various experimental procedures in the real and the virtual world.

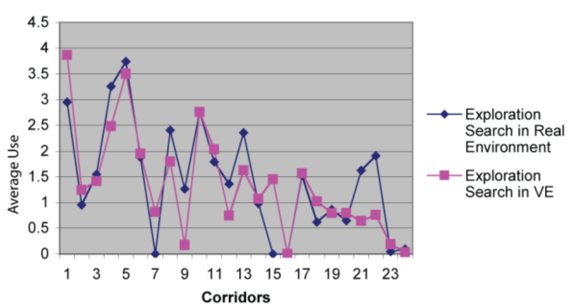

Figure 7: Average use of corridors in open exploration

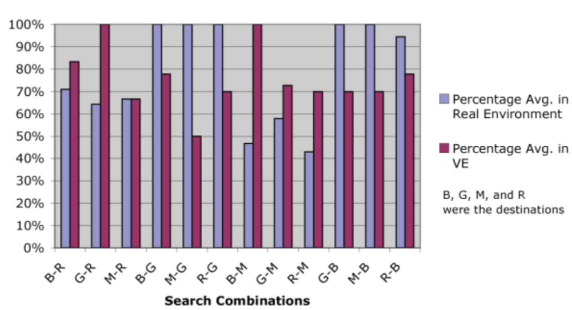

Figure 8: Percentage of wayfinding success

The, correlational analysis of corridor use data and integration-3 values between virtual and real hospitals were also remarkable similar. The scatter-grams and values are shown in figure 9 a and b. A side by side comparison shows that they are not only statistically similar, i.e. their r values are very close (TUC pair .775 and .725, TURC pair .657 and .692. Figure 9a and 9b), but also, the scatter plots are very comparable. Finally, appearance of corridors in the sketch maps drawn in both the real and the virtual environment was correlated with integration-3, and these too were very similar (see figure 9c). *These results support the argument that topological configuration, as modeled by Space Syntax is an important predictor of both exploration and wayfinding behavior in real and virtual settings.* This is especially significant when we remember that one set of data was obtained in a virtual setting where all kinds of extraneous environmental variables were controlled and layout was the only predictor. The importance of topological configurational variables in wayfinding and spatial cognition is not a new proposal and has been reported before (Haq, 2003; Haq & Zimring, 2003; Kim, 2001; Kim & Penn, 2004; Kuipers, 1983; Ortega-Andeane, Jimenez-Rosas, Mercado-Domenech, & Estrada-Rodriguez, 2005; Peponis et al., 1990; Willham, 1992) What is novel is the fact that the same experimental procedures when undertaken in a real and a virtual environment have produced very similar results (Haq, Hill and Pramanik, 2005).

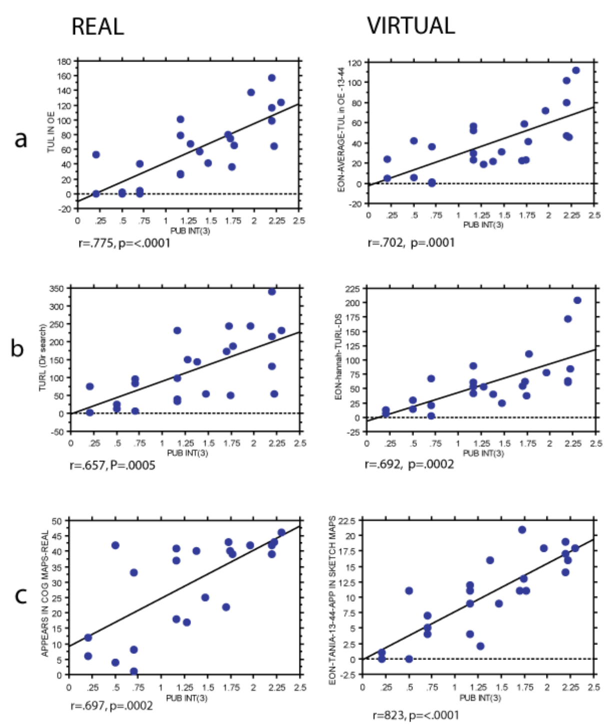

Figure 9: Comparison of correlations between experimental data and Integration-3 in real and virtual environments.
a. Integration-3 with TUC, b with TURC and c with Appearance in sketch maps.

The analyses also provide clues towards the distinction between topological and Euclidian configurational learning. Pointing to previously visited but unseen destinations and sketch mapping of the corridors are indicators of Euclidian learning. The average pointing error inside the real building was 39.52 degrees while inside the VIR it was 56.03 degrees. Sketch map accuracy in the real building was 57.92 degrees compared to 37.5 degrees in the VIR. Furthermore, two-sample t-tests assuming unequal variances revealed a substantial difference between the two data sets (p-<.0079 for pointing errors and p=.0006 for sketch mapping accuracy, see table 2). Therefore it can be safely assumed that *Euclidian learning in the virtual environment was less than that in the real world*. Thus, one might say that in an environment devoid of all other cues except layout, and where FOV was only 61 degrees, Euclidian understanding develops slowly. On the other hand it has been demonstrated that wayfinding successes were similar and so was the reliance on topological configuration.

5 FINAL COMMENTS

This is perhaps the first attempt to compile data obtained from exploration, wayfinding and cognitive tests in both a real environment and its virtual counterpart. Furthermore, the virtual world was developed to control all kinds of extraneous variables so that the plan remained the only independent variable. This was highlighted further by the VIR *not* being fully realistic; it did not provide all environmental properties and nuances; nor did it provide a reasonable human field of vision (FOV). Nevertheless, the results show that the two environments produced similar wayfinding behavior when considered from the point of view of the plan. Topological configuration values of corridors obtained by Space Syntax analysis of building plans predicted about 49% of wayfinding and exploratory use of those corridors. In other words, higher the configurational values, the more they are likely to be used. Admittedly more experimentations and comparisons need to be carried out; but one aspect stands out clearly. This is that a building plan, especially the corridor layout, has a tremendous influence on the way spaces will be used by visitors. Since a similar pattern was seen in three real hospital buildings and one virtual environment, and in previous reports by Peponis, Zimring and Choi, (1990) and Kim and Penn (2004), there can be substantial credence to the fact that the plan matters in a significant manner to immersed visitors in a large building. The layout and its topological configuration provide the framework for ‘natural’ movement and wayfinding. Since layout analysis can be done easily from a plan drawing, even before more detailed design is developed, architects may avail the opportunity of testing their initial designs from the perspective of an immersed visitor and make adjustments accordingly for wayfinding friendly designs. Additionally, overall shape of the plan and corridor system, distribution of public and private areas, locations of desks, kiosks etc. and other design features may be investigated with confidence.

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