Environmental Modeling: Using Space Syntax in Spatial Cognition Research

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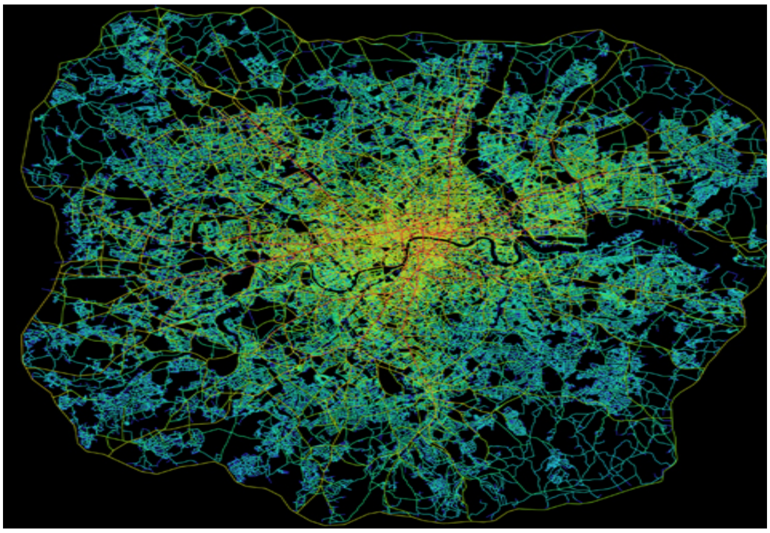
Spatial cognition is concerned with both internal mental processes and external environments. It is from our surroundings that we acquire much of our spatial knowledge, and it is through those surroundings that we navigate. The interplay between, on the one hand, the sensory information and the physical constraints provided by the surrounding environment, and, on the other hand, humans' perceptual and cognitive processes is central to the questions of spatial cognition.

Yet, for all the field's success at using precise behavioral measures to study spatial memory, cognitive models to study wayfinding, and virtual reality to study locomotion (to cite only a few advances), spatial cognition research has given insufficient attention to the role of environmental surroundings. In part, this has been an issue of competing concerns: When forced to choose between precise behavioral measures and rich, ecologically valid environments, researchers with training in experimental psychology will likely select the former and substitute for the latter a simple, contrived laboratory setting.

In fact, this is more an issue of methodology: Many spatial cognition researchers know how to design careful experiments that yield behavioral (and now even neural) measures that differentiate between competing psychological theories. More difficult to find in the spatial cognition literature are similarly rigorous techniques for characterizing environments and their perceptually and cognitively relevant properties. With no accurate instruments for measuring environments, it is no wonder that we have focused primarily on internal processes—at the expense of external environmental factors.

Vitruvius presenting *De Architectura* to Augustus. (Wikipedia)

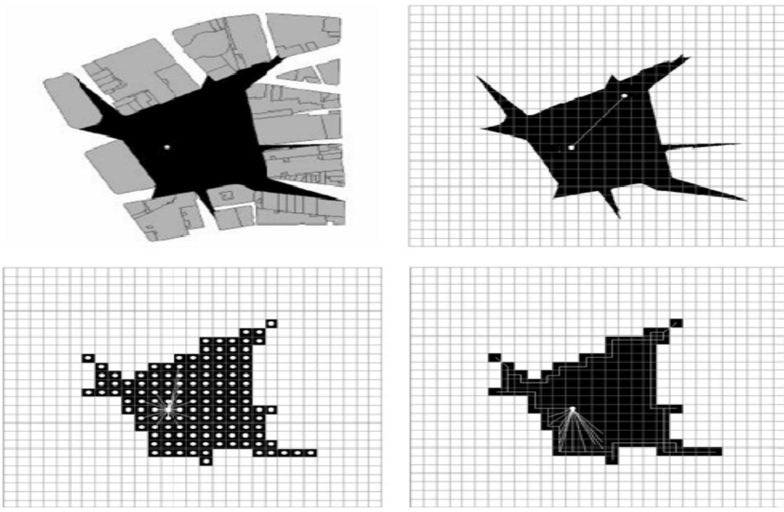
The fields of architecture, urban design, landscape architecture, and city planning all have both a professional and a theoretical interest in the matter of physical environments, particularly built environments. Since at least the days of the Roman architect Vitruvius, environmental designers have taken a formal, patterned approach to designing and understanding buildings, cities, and landscapes. And with the rise of computers, these theories of architectural form and urban structure have inspired synthetic algorithms for creating new designs and analytic approaches for understanding design plans and actual environments. It is the latter that are of particular relevance to spatial cognition, as it is with these tools for environmental



London represented in an axial map.
(Space Syntax Limited)

analysis that spatial cognition researchers can bring to external environments the same level of concern they bring to internal processes.

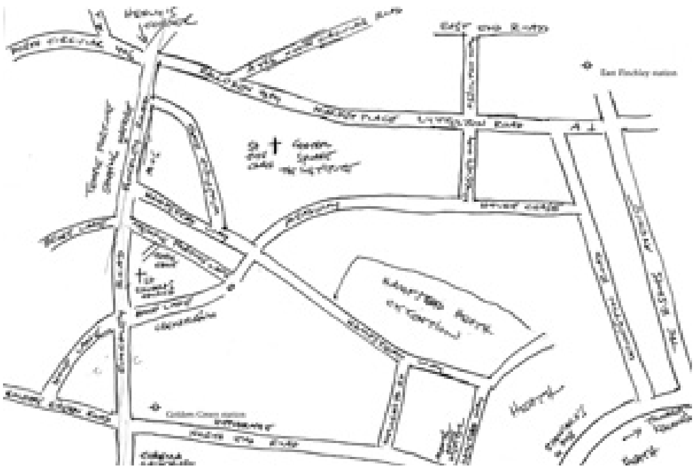
Within the environmental design fields, a number of complementary techniques have been developed for modeling environments. Space syntax, conceived by Bill Hillier, Julienne Hanson, and their colleagues at University College London (1984), originally to capture spatial patterns of settlements using a connected graph of *axial lines*, now offers a wide selection of models and measurements for characterizing building interiors, outdoor landscapes, and entire cities. UCL has trained a generation of architects to use these modeling approaches in their practices, and researchers now come together every two years for the well-attended Space Syntax Symposium. Also originating in the United Kingdom is the modeling concept of the *isovist*, the region of space visible from a given point (Tandy, 1967). Space syntax analysis and isovist analysis have been integrated, more recently, in *visibility graph analysis*, which connects together mutually visible points in a graph data structure (Turner, Dox, O'Sullivan, and Penn, 2001). A note on disciplinary distinctions: Many of these computational approaches have developed in parallel with those in computer science (particularly in robotics) and in geographic information science (where isovists are better known as *viewsheds*).



Generating an isovist using a visibility graph.
(Batty, 2001)

Combining these environmental models and the measures they produce with behavioral measures, collected using the well-tested methods of experimental psychology is a promising approach to studying the interplay of internal processes and external environments. In recent years, this line of research has been featured in a special issue of *Environment and Behavior* (Issue 1, 2003), the Space Syntax and Spatial Cognition workshop at Spatial Cognition 2006, and the Cognitive Approach to Modeling Environments workshop at GIScience 2006, in addition to an increasing number of papers in publications like the *Journal of Environmental Psychology*, *Environment and Planning B: Planning and Design*, and *Spatial Cognition and Computation*. Some representative findings include:

- When analyzed using the axial-map modeling techniques of space syntax, residents' sketch maps of neighborhood streets showed similar "integration" values as those of the streets in the real environment, suggesting that the axial-map model and the residents' spatial knowledge are capturing similar environmental properties (Kim & Penn, 2004)
- When exploring a hospital, also modeled using axial-map techniques, participants initially traveled according to local topological properties, yet over time, their travel patterns began to correlate more strongly with "integration" and other global measures, suggesting that spatial learning attunes people to the larger organizational characteristics of environments (Haq & Zimring, 2003).
- Similarly, when navigating through a complex building, novices chose travel paths that were more visually connected and "integrated" than experts, who were more likely to take hidden routes (Hölscher, Brösamle, and Vrachliotis, 2006).
- When attempting to reach a destination on the other side of an elaborate virtual environment, participants applied a navigation strategy that minimized the angular difference between their route heading and the perceived bearing toward their destination (Conroy Dalton, 2001).



One participant's sketch map of a neighborhood. (Kim & Penn, 2004)

With this combination workshop and tutorial (held on 15 August 2010 as part of the International Spatial Cognition Conference in Mt. Hood, Oregon), we sought to build on these past successes by:

1. equipping cognitive scientists to use environmental models as part of their spatial cognition studies, on their own or through collaborations;
2. continuing the ongoing discussion of standardizing our methodologies for combining behavioral studies of spatial cognition with computational models of environmental form;
3. and working toward a common vocabulary among the spatial cognition, space syntax, and geographic information science research communities.

This primary audience of this workshop/tutorial was spatial cognition researchers with strong training in behavioral or computational methods but, most likely, little training in environmental modeling. We hope to hold a complementary workshop/tutorial at the next Space Syntax Symposium (2011 in Chile), in which we will offer experts in environmental modeling an introduction to behavioral research methods and continue to pursue this line of collaborative, integrative research.

In the meantime, the following papers summarize well the current promise and challenge of research that models environments in order to better understand the cognition and behavior of individuals and the design of their surroundings.

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Contents

Visibility and wayfinding: a VR study on emergency strategies

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Abstract. The present work aims to investigate the role of 3 factors related to the environmental configuration in emergency wayfinding strategies. In particular, it moves from the results of a previous real-world study in which visibility, in particular, seemed to be the most influent factor in influencing wayfinding strategies. Angular incidence, in turn, played a –minor- role, whereas metrical distance was the less used criterion. These outputs appeared to deserve to be more deeply studied, so that two VR experiment were designed to better control environmental variables and to compare the results obtained in different situations. Results confirm the role of Visibility and Angular Incidence in influencing participant's wayfinding strategies.

Keywords: wayfinding, angular incidence, visibility, emergency strategies

1 Introduction

The present work targets the relationship between spatial configuration and wayfinding. It focuses, in particular, on the influence of two main environmental variables: visibility and angular incidence. The different factors implied in the wayfinding process in the built environments have to be investigated taking into account their complex nature. That is why they have been intensively investigated by scholars (Conroy Dalton et al. 2009). Wayfinding process is not only influenced by personal factors, but also by environmental factors. These factors can influence people's strategies. According to literature, some of these variables are:

- Metric distance, that can reflect in the, so called, shortest paths strategy (Hillier and Iida 2005). It is one of the fundamental factors taken in to account for the design of emergency exits and YAH (You-Are-Here) maps;
- Angular incidence, that can result in the least angle strategy (Conroy Dalton 2003);
- Visibility, since people can develop their displacement and wayfinding strategy also basing on the number of elements of the path that they can perceive, as an answer to the environmental affordances (Gibson 1979, Turner 2007).

The importance of these 2 last variables, in particular, was stressed by previous studies (Nenci and Troffa 2006, 2007; Conroy Dalton et al. 2009).

Some other factors, related to the nature of the task, can influence people's displacement when they have to *find their way* in a built environment and, mainly, inside a building. One of these factors can be the need to complete the task in a hurry (Hölscher et al. 2007); this can be particularly important when approaching the topic of emergency exits and maps (Klippel et al. 2006; Hölscher et al. 2007).

The present work moves from the outputs of a previous study (Troffa and Nenci, 2009), carried on in a *real-world* condition, which aimed to investigate the effect of visibility, angular incidence and metric distance.

The indoor environment adopted as the setting of the previous study was chosen because of its peculiar structure, that allowed to arrange 2 different experimental conditions and to obtain a clear distinction of the involved variables in the experimental design. In the first experimental condition, participants had to choose between a first shortest option, and a second -longer- option, characterized at the same time by the highest visibility and by the least angular incidence. Participants significantly chose more frequently this second route. In the second experimental condition, participants had to choose among three separate options: a shortest route, a least angle route and an highest visibility route. Participants preferred the route characterised by the highest visibility, then the option characterised by the lowest angular incidence, whereas the lowest frequency of choice was associated with the shortest route.

Starting from these outputs, the present work presents 2 different studies, carried out in a Virtual 3D environment.

2 First Study

Two different experimental conditions were prepared (2 Scenarios), basing on the original structure of the building used in the previous work:

- In the first experimental condition (1st Scenario), participants had to choose between 2 different routes: a shortest route (a) and a longest route characterized at the same time by the highest visibility and by the least angular incidence (b).
- In the second experimental condition (2nd Scenario), participants had to choose among three possible options: a shortest route (a); an highest visibility route (b) and a least angular incidence route (c).

The degree of visibility was operationalized by basing on the part of environment that can be perceived from the decision point. It was valued through a pre-test, by asking to a sub-group of participants (n=15) to furnish an esteem of the level of visibility of the different paths.

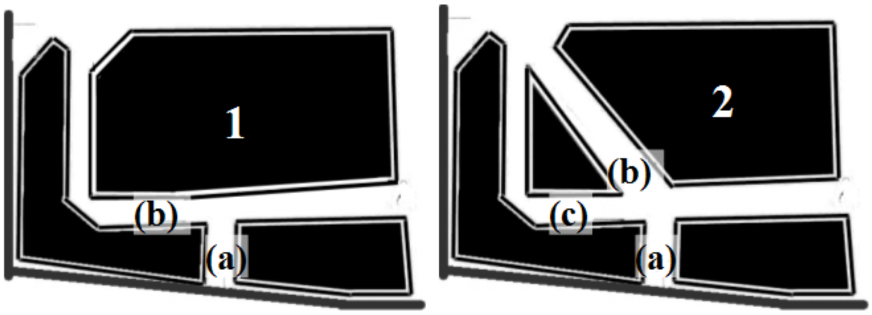

Fig. 1. The maps representing the 2 Scenarios of the first study. The first experimental condition (1st Scenario; 1) with the options (a) and (b); and the Second experimental condition (2nd Scenario; 2) with the options (a), (b) and (c). The borders on the left and on the bottom represent the outside.

2.1 Method

2.1.1 Participants

The study involved n=30 inhabitants of the city of Cagliari (Sardinia, Italy). The sample was balanced regarding the gender variable, and for as regards the degree of familiarity with the original real setting used as a base for the 3D environment (high *vs* low).

2.1.2 Procedure

Participants started from a common origin point. They all were requested to reach the outside in the fastest way, as if they were experiencing an emergency. By virtue of the structure of the setting, the path's decision had to be taken in a single, common, point. All the possible paths connecting the starting point to the destination were homogenised for as regards the appearance, since the walls presented no complex texture (they were homogeneous and uniform walls).

The 3d setting was realised by reproducing the real environment by means of a freeware 3d engine software. People can move within the environment through the use of keyboard and /or mouse.

No multi-level strategy was possible (e.g. see Hölscher et al. 2006, 2007).

No people was represented in the environment, in order to control the possible influence of the presence of *others* (Zacharias 2001; Conroy Dalton et al. 2009).

Participants have no time limit to complete the task; they all took less than 2 minutes to reach the outside.

Participants were requested to perform a cognitive and wayfinding test (Saracini et al. 2008) in order to explore the influence of wayfinding ability on the task.

After concluding the task participants were asked to answer a brief questionnaire targeting their knowledge of the environment and their awareness about the different possible routes. Participants with an high level of familiarity were aware of the possible exits (86.66% of them).

2.2 Data analyses

Since the focus of the study was on categorical data (frequency x typology) a log-linear analysis was performed to investigate possible associations among the frequency of choices and the different experimental variables.

2.3 Results

Results confirm the outputs of the previous study. In the 2 options condition (shortest option *vs* highest visibility & least angle option) participants significantly chose more frequently the longest route characterised by the highest visibility and by the least angular incidence ($z = 4.078$, p\0.05). In the 3 options condition (shortest route *vs* least angle route *vs* highest visibility route), participants chose with a significantly higher frequency the route characterised by the highest visibility ($z = 3.687$, p\0.05), then the option characterised by the lowest angular incidence ($z = 1.268$). The shortest route was the less chosen ($z = -2.834$, p\0.05). Familiarity do not seem to affect participant's choices. Coherently with the results of the previous studies, there was no effect of cognitive spatial abilities (p =n.s.).

Table 1. Frequency of choice for any route in the 2 Scenarios of the first study

Scenario	**Route**		
	(a)	(b)	(c)
1st Scenario (2 Options)	0	30	/
2nd Scenario (3 Options)	0	20	10

3 Second Study

Since the visual 3d setting was developed from an actual building, not any configurational feature was controlled, especially for the 3-choices condition. Actually, configuration was controlled up to the point in which participants had to make their decision. Some differences exist in the following part of the routes. In particular, the shortest way takes directly outside the building, whereas both the two longer routes involve a mandatory turning after the point of decision. Al-

though these turnings do not involve a decision making on the part of the participants, since they have no further choices to make besides the single point of decision, it can be hypothesized that these differences can have an effect on participants' choices.
For this reason, a new virtual 3D setting was designed by modifying the 2nd Scenario of the previous setting in the way to reduce the differences between the 2 routes.

3.1 Method

3.1.1 Participants

The study involved n=30 inhabitants of the city of Cagliari (Sardinia, Italy). The sample was balanced regarding the gender variable.

3.1.2 Procedures

Participants had to choose among three possible options, in a single Scenario: the shortest route (a) theleast angular incidence route (b) and the highest visibility (c).
The walls of the 3D setting were homogeneous and uniform walls, so that all the possible paths were characterized by an homogeneous appearance.
Participants started from a common origin point. They all were requested to reach the outside in the lowest possible time, as if they were experiencing an emergency.
Given to the structure of the setting, the path's decision had to be taken in a single, common point.
The 3D environment represented a space with no people.
Participants have no time limit to complete the task; they all took less than 2 minutes to reach the outside.
Participants were requested to perform the same cognitive and wayfinding test of the first experiment (Saracini et al. 2008).

After concluding the task participants were asked to answer a brief questionnaire targeting their knowledge of the environment and their awareness about the different possible routes.

3.2 Data analyses

A log-linear analysis was performed, to investigate possible associations among participant's choices and the different experimental variables.

3.3 Results

Results of the second study reflect those of the first experiment. Modifications to the part of the setting subsequent to the decision point seem not to affect the outputs. Participants chose significantly more frequently the highest visibility route (z

= 3.549, p\0.05), then the option characterised by the lowest angular incidence (z = 1.540), while the shortest route was the less chosen (z = -3.400, p\0.05). There was no effect of cognitive spatial abilities (p = n.s.).

Table 2. Frequency of choice for any route in the single Scenario of the second study

Scenario	Route		
	(a)	(b)	(c)
2nd Scenario (3 Options)	1	17	11

4 Discussion

These outputs seem to stress once more the importance of the configurational features of the environment for wayfinding. There was an homogeneity of results between the *real world* study and the *VR* study. This confirms the possibility to approach these topics in a *VR* mode, mainly when it can be used to design settings that will allow to control and manipulate the environmental variables (and obviously the environmental configuration). It seems to be confirmed the role of visibility and angular incidence in influencing wayfinding behaviour, even in an emergency. When visibility and angular incidence are present together, as in many real-world cases, participants base their strategy more on these 2 variables. When these 2 variables are distinguished in the experimental design, visibility appears to be the more powerful factor. Coherently with past studies, these variables seem to act independently from the cognitive abilities of the participants. People seem to be influenced by spatial configuration, whether they have an high or low degree of spatial ability.

This work approached the topic of emergency exit strategies. Outputs stress how people seems to prefer highest visibility (and/or lowest angle) strategy to shortest route strategy, even when they have to reach the destination in a hurry. These should have important practical implications, mainly in context (as the one represented by the nation in which this studies were carried out) when the metrical factor is the only important factor taken into account by the laws for as regards the YAH maps. In fact, as Klippel et al. (2006) suggested, the principle and concepts of spatial cognition are generally not taken into account in the design of YAH maps. In particular, this output could suggest an important aspect for as regards the design of emergency routes and public spaces, in the moment in which a rapid escape and flow has to be allowed. Future studies would have to approach this topic, through an higher level of control of the degree of paths' knowledge of the participants, to better control the influence of the variables. Actually, the studies presented in this paper could be integrated by further investigations in which the awareness of the different variables (i.e. the metrical) is more clearly controlled.

Visibility (as Angular Incidence) seems to operate equally in the first and in the second study, so that the configuration of the node where people have to take the decision seems –in these studies- to be more salient than the configuration of the following part of the route. But, obviously, these output deserves to be further studied, since literature suggests that the whole configuration of the setting could influence this kind of spatial behaviour. In the light of these considerations, further studies should have to be planned, paying more attention to the differences in the spatial configuration of the settings and controlling these variables in the VR settings. In particular, formal assessments of environmental characteristics (as Space Syntax measures or others) could be helpful to more formally describe the configurational characteristics of the routes. Another aspect that would take advantage from a more formal analyses of the setting is visibility. The present work based the measure of visibility on participant's perception and evaluation. To include in future studies measures as depthmap's vga analysis or isovist analysis could lead to a better control of the experimental setting.

Furthermore, the presence of others can be manipulated as an experimental variable, to increase the number of factors considered in the studies.

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The other way.
Phenomenology and participatory design complementing space syntax in research for: design for movement

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Abstract. This theoretical article looks at some of the possible reasons for the continuing gap between research on and design for human movement and suggests participatory design as an approach that, paired with phenomenology, could complement space syntax in research for design for human movement. The article opens with a brief recap of cognitive spatial research on human movement, focusing on some of its assumptions that might limit the possibilities of closing the gap between research on and design for movement. Space syntax theory and methodology is briefly presented as the approach that has been successful in overcoming some of the limitations of cognitive science tradition. In the following section I discuss phenomenology and participatory design as theoretical and methodological paradigms that could complement the space syntax approach in the service of research for design for human movement.

Keywords: **s**pace syntax, research for design, participatory design, phenomenology

1 Research and design for movement

Human movement is perhaps a self-explanatory term and therefore is rarely defined in literature. Those few who do define it, understand it as *any spatial displacement of the body or bodily part initiated by the person himself* [herself] [1:148]. In other words, in can be understood as deliberately walking or making one's way through some space. Such intentional bodily movement can include, among others, travel between known places, navigation to novel destinations, or exploration with no specific destination. This rather broad term needs to be differentiated from the term wayfinding often used in literature on movement. Wayfinding is usually defined (see for example [2] and others) as finding one's way from an origin to a destination. Allen further defines it as *purposeful movement to a specific destination that is distal* and, thus, cannot be perceived directly by the traveler [ibid:47]. In this sense, finding one's way (wayfinding) is also making one's way, and it falls into the category of

movement as an intentional act of making one's way through the space. The term movement, however, encompasses other types of making one's way through some space, such as exploration, or movement to known destinations.
The environmental design (ED) has embraced the phenomena of movement and wayfinding. Available literature on ED for human movement is substantial, with some specific topics clearly emerging: (1) the field of universal design with respect to movement for people with disability [3-5], (2) substantial literature from the fields of design and graphic design which mostly focuses on wayfinding solutions (such as signage) and not the physical environment itself nor on human experience in space [see for example: 6], (3) another topic, that has gained a lot of interest recently from both researchers and practitioners is the walkability of urban spaces. This body of literature is a fascinating account of research directly applicable for the urban design for human movement [7-9].

Taken that the everyday movement is happening inside buildings perhaps even more than in urban spaces, one would expect that the same interest would be devoted to producing research directly applicable to the design of architectural space. Indeed, the goal for environment behavior (EB) studies was set by its founders to be finding *solutions to pressing environmental problems* [10] and as such providing foundations for design guidelines. At the same time, from the very beginning of the field, both architectural research and studies of human movement have been in the center of attention. The first Environmental Psychology textbook [11], for example, did in fact lay out the basis for architectural research in a number of pieces. Winkel and Sasanoff [12] for example, examined the possibilities of laboratory research that could be diagnostic for architectural environments. Others introduced a number of methods for studying behavior in environments at different scales (from home spaces through institutional settings to urban scale); Bechtel, for example, summarized methods for the study of movement in architectural space [13], Ittelson et al. [14] introduced behavioral mapping and Lynch and Rivkin [15] described the method that is now know known as a transect walk. In other words E-B studies/Environmental Psychology has been from the very beginning focused on studying human movement in architectural settings and was set up as an applied field with the hope that the research would provide and point to solutions for environmental design (ED) and in particular solutions for the design for movement in built environment.

Indeed, social science, and especially environmental social science, has addressed the issue of human navigation and wayfinding through the lenses of its different disciplines. Psychology has provided insights into the cognitive processes, directing decisions made by people as they move through their environments [16][17][2], how they are influenced by sex and individual differences [18] and strategies that are employed [19]. Geographers and urban planners have examined how we construct and use mental maps [20]. We now also know more about the development of spatial cognition [21] and route and spatial learning [22] to mention just a few of this rich body of literature.

However, so far research on human movement, with a few exceptions, has been more successful in generating theory than in producing potential applications for environmental design [23:5]. In fact this (self-)critique is not unique for researchers studying movement, but it quite common across the whole field of environment-behavior studies. Because the focus of this paper is specifically on research and design for movement and because the broader issue of gap between research and design has been taken up elsewhere [24] I will not get into a detailed discussion here, but just point out that perhaps some of the proposed reasons for the gap between research and design and critique of the research model in general could be relevant to the research and design on movement in particular. Lang [25] and Ward [26] argue for example that the gap between research and design might stem from the lack of a successful means of communication between the two: designers have often been blamed for not appreciating the research, "knowing better", and seeing the design process as merely expressions of their creativity while researchers have been blamed for not communicating their findings in an easily accessible and applicable format.

From the postmodern perspective EB research has sometimes been criticized for its urge for generalizable and universal findings that could be used across different settings, while in fact design is never a process from "nowhere" [27]. Design, just like knowledge is always "from somewhere", situated within a particular context, and no universal formulas can describe or answer the complex environmental realities.

On methodological level, it has been argued that the behavioral research model in general, has not been very successful in facilitating collaboration among researchers, designers, and planners, exactly because it separates research and application [28]. This is also often true for the research focusing on human movement. More often than not, we conduct the studies on human movement and navigation in environments that have already been designed, constructed and occupied.

On an epistemological level, the positivism of E-B research and environmental design has been questioned and criticized for assuming the *neutrality of scientific rationality* and of the researcher, as well as *separation of subject and object,* [and] *of facts and feelings* [29:70]. This point is in particular relevant to research on human movement in architectural settings, as spatial cognition researchers conceptualize movement and navigation as having behavioral and cognitive components [30]. In other words the totality of human experience of moving through a space is reduced to human behavior and cognition. As Hillier points out, *[t]raditional models have always use simplified assumptions about human cognition and behaviour [...] as a result, such models have been as far removed from the <u>experience</u> of living in the city as they have been from practical design* [emphasis added, 31: 30].

Just as a lot of other EB research, vast amounts of the research on movement within the spatial cognition are based on an underlying assumption that the environment is represented in the form of cognitive maps and it is the cognitive maps that humans act upon when moving though their environment. This assumption has been disputed from different perspectives (for more on the problematic concept of cognitive maps see for example Ingold [32]). Regardless of which position one takes in this argument, clearly this assumption coincides with, if not leads to the preoccupation of the cognitively oriented research on movement with mental representations of the environment and not the environment itself, while in fact, as Heft points [33] out after Wohlwill, *Environment is not in the head* [34]. As a result, just as researchers from within this tradition admit, *spatial cognition research has given insufficient attention to the role of environmental surroundings* [35:12] and thus has been more successful in generating theory than in producing potential applications for environmental design [36].

To sum up, the main issues that I would like to point to as perhaps underlying the gap between research and design for human movement within architectural settings would be:

1) separation of and the lack of proper communication between research on movement and design for movement itself
2) separation of research and design from a particular context of the design project and the multiplicity of its users experiences,
3) reductionist conceptualization of the experience of spaces through movement to behavior and cognition,
4) preoccupation with mental representations of the environment (mental maps) and not the actual environment,

These issues do not necessarily have to be seen as shortcomings, but I would argue that if one assumes that the goal of the research on movement is to provide findings applicable and easily translated into design guidelines, they should be addressed.

2 Space syntax contribution to research for design for movement

Space syntax theory and methodology developed by Bill Hillier and his colleagues at The Bartlett, University College London is an approach that overcomes some of the issues mentioned by stressing the role of the actual environment for human movement (and vice versa) and does not merely focus on wayfinding. The lens that space syntax provides is in fact not a "traditional" spatial cognition perspective. Instead, space syntax is in fact a socio-spatial theory, which theoretical basis could be, if not traced, then in some ways drawn parallel to Giddens' structuration theory, emphasizing the mutual and dynamic co-construction of the spatial and the social [38]. The methodology developed is a structural analysis of space, quantifying it in terms of visual accessibility (or vistas available to users) and the connectivity of its parts. This analysis has been linked to path choices (or in other words, predicting - to some extend - where people walk) and other phenomena such as crime [39], property values [40], congestion and pollution [41].

Space syntax as a theory does in fact overcome some of the issues quoted before. As Montello [42] points out in his overview of space syntax contribution to environment behavior studies (or environmental psychology), the theory escapes the preoccupation with the mental representation of the environment, focusing instead on the human acting "on" the actual environment and the visibility of spaces (vistas). The method provides a powerful tool for analysis of connecting the spatial configuration and the vistas it provides for human movement [42: 12]. One could perhaps argue that it is the focus on the actual environment and not its mental representations that has allowed for easier translation of the research to design and has led to a vast body of applied work done by the Space Syntax Ltd.

But as Montello argues, space syntax almost completely disregards qualities of the physical environment other than configurational such as colors, textures, patterns or landmarks. What is more, while providing insights into the role of topological configuration for human experience and movement, it disregards as irrelevant the metric qualities of the environment. In other words, space syntax methodology does shift the focus of spatial oriented cognitive research from the mental representation to the actual environment, but the lens it takes on the environment filters out many qualities potentially relevant for the design for movement.

3 Space Syntax and Phenomenology

Space syntax is perhaps the most prolific approach today providing research for design for movement, and narrowing the research design gap. However, it does not as of yet, overcome all the limitations noted. Taken the shortcomings highlighted in the existing literature, how can the gap between environmental social science's research on movement and environmental design be addressed?

Space syntax has always been appropriated by the spatial cognition researchers, who conceive human movement as having cognitive and behavioral components. But space syntax was in fact conceived as a social theory and methodology to study how space appears and is **experienced** by humans - experienced and not perceived or cognitively represented. In other words, space syntax does not inherently call for reducing the experience of movement though space to behavior and cognition. Instead the authors talk about experience [of the movement through the world] as a whole. This conceptualization opens up the possibility taken up both by Seamon [43] and Hillier [44] to align the space syntax theory with phenomenology, which is a study of human experience in the world. In fact, Seamon argues that space syntax *has immediate relation to the phenomenological vantage point because [it] recognizes how a world's underlying spatial structure guides particular actions and circulations of human bodies moving through that world and, how, in turn, a self-conscious understanding of this human world/physical world intimacy might lead to environmental design and policy that supports a stronger sense of place and community* [43: 40].

Both Seamon and Hillier point to compatibilities of the two, seemingly very different, approaches. Seamon proposes to complement space syntax with phenomenological research, where phenomenology is ... *the exploration and description of phenomena, where phenomena refers to things or experiences as human beings experience them* [45]. Complementing space syntax with a phenomenological approach would allow for arriving at the invariant qualities that underlie the phenomena of experience of movement in the world. This would in turn allow for enriching *the incomplete view of the relations between human beings and their created environments,* [that space syntax provides] [44:12] and perhaps even for overcoming some of the limitations of space syntax that Montello was concerned about [42]. But can it lead to narrowing the gap between research on and the design for movement?

This phenomenological paradigm has been argued to have the potential of contributing to environmental design research by opening it up to a variety of dimensions of human experience of environments [46], potential that has not been yet fully utilized in the research on human movement. I would however argue that while this contribution is needed to expand the picture, it does not have the potential of fully closing the gap between research and the design for movement. The argument would be that since phenomenological research focuses on the experience (though in a more holistic manner than spatial cognition oriented research) it does not easily provide possibilities to translate the data into design for movement.

4 Participatory Design in service of research and design for movement

Phenomenological preoccupation with human experience paired with the topological configuration of space syntax calls for yet another mode/approach that would allow for more focus on the actual environment and it's (other than configurational) qualities. As already mentioned over the past decades there has been a growing disappointment with the gap between research and design. It has been argued that, in general, the behavioral research model that separates research and application has not been very successful in facilitating collaboration among researchers, designers, and planners precisely because of this separation [47]. Phenomenology and space syntax (though in a lesser degree) separate the two, providing research results that can inform the design (can, but not necessarily do).

This is why I would want to argue for participatory design as an alternative research approach for design strategy to overcome this failure of environment-behavior studies. Though participatory design has never before been utilized in research on movement, it has been argued to have a potential to complement the phenomenological approach and could be applied in research on human movement. In particular, Saegert points out [46] that while a participatory approach is rarely a part of phenomenological research, it is implied in phenomenology and it could be used to argue for greater user participation in environmental design.

But what exactly is PD? Researchers and practitioners with varied background s practice PD, in different fields: architectural design and urban planning, geography, and system development. Despite the wide use of the term itself, there seems to be no clear consensus in the literature on what PD is. Some call in an attitude (attitude about a force for change in the creation and management of environments for people: [47])

a tradition, movement [48], a social, ethical and political practice [49], or research methodology [50]. Horelli even states that PD is a typical "mess" of late modern times that seems to involve a set of interconnected problems that are difficult to conceptualize and analyze [49]. However, its “messiness” and the fact that PD cuts across disciplines and cultures, is where PD’s strength lies [48].

How can PD contribute to the space syntax and phenomonology in service for research for the design for movement? In the light of postmodern critical thought I would argue that space syntax is a positivistic theory, aiming to discover the universal truths and provide universal design solutions, while in fact design is never a process from “nowhere” [27]. This is where PD allows us to create the connection between the analysis of configurational properties and individual experiences of users with actual design solutions, allowing for research for design.

There is usually a consensus among practitioners that PD is design, aiming at democratization [planning, architectural design, system development, policy making], which allows for involvement of those affected (user’s, citizens, or just people) and their mutual learning. But can we actually make a claim that PD could serve as a research methodology? I would like to follow Spinuzzi’s understanding of PD, where he claims that participatory *design IS research* [50]. Just as participatory action research (PAR) is research, so is PD. Participatory action research is conceived as a methodology for advancing scientific knowledge through achieving practical objectives. In that sense it is an applied approach, oriented at change. Similarly PD is a change oriented research process, in which in which tacit knowledge is revealed in group knowledge co-construction and through doing/making. In other words, with PD, research happens through making, doing, designing and allowing tacit knowledge [51] to surface.

Introducing participatory design into an approach to researching (for design) for movement would allow us to overcome the issue of separation of research and design. By introducing research by (participatory) design into the space syntax methodology and practice, we also leave space for situating the design within a particular context, while bringing the focus from the individual to the environment and application.

Triangulating a phenomenological approach using qualitative methods with research by (participatory) design and a space syntax approach addresses the issues that traditional cognitive approaches to studying movement in architectural settings have been facing. What will follow this theoretical article is a study on an actual design situation for a new office building. The study employs walk-through ethnographic methods to study movement experience of users that will be relocating to the new building. This thick description of both individual experiences of movement and the specific environmental qualities that are associated with them will be overlaid over the space syntax analysis of existing spaces. Similarly, the space syntax method will be used for analysis of the new building, whose spatial configuration is already designed. Participatory design sessions about the interior of the new building will serve as the third method bringing the focus to the actual physical environment within a particular context.

Warning: The research might get “messy”, as there doesn’t seem to be any other way to do it but to get ones hands dirty, if one decides to step out of the laboratory setting.

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Turning the shelves: Empirical findings and Space Syntax analyses of two virtual supermarket variations

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Abstract. The spatial structure of a virtual supermarket was systematically varied to investigate human behavior and cognitive processes in unusual building configurations. The study builds upon experiments in a regular supermarket, which serve as a baseline case. In a between-participant design a total of 41 participants completed a search task in two different virtual supermarket environments. For 21 participants the supermarket shelves were turned towards them at a 45° angle when entering the store, giving high visual access to product categories and products. For 20 participants the shelves were placed in exactly the opposite direction obstructing a quick development of shopping goods dependencies. The obtained differences in search performance between the two conditions are analyzed using space syntax analyses and comparisons made of environmental features and participants' actual search path trajectories.

Keywords: Spatial Cognition, Space Syntax, Virtual Reality, Obliqueness.

1 Introduction

Finding one's way in a complex spatial environment can be considered a cognitive process of problem solving and decision-making. Authors like Passini (1981) emphasize that wayfinding entails the planning and execution of a sequence of movement decisions. These movement decisions are influenced by a number of factors, including familiarity with an environment and—quite prominently—the geometric structure of the environment. General background knowledge about typical configurations of objects in an environment can also influence such decision making, for example in a supermarket where shoppers typically know which products tend to be located close to each other. In the present study we investigate the relative impact of geometry and background knowledge and potential interactions between the two by systematically changing the geometry of a virtual supermarket.

The advent of virtual reality has propelled research on human spatial cognition. Of course, just as with every methodology the use of computer-generated environments has benefits (Ruddle, Payne & Jones, 1997) and drawbacks. However, one of the greatest advantages is the ease with which environmental features can be altered. We make use of this possibility by changing the layout of a virtual supermarket (see figure 1) whose basic layout had been investigated in previous studies.

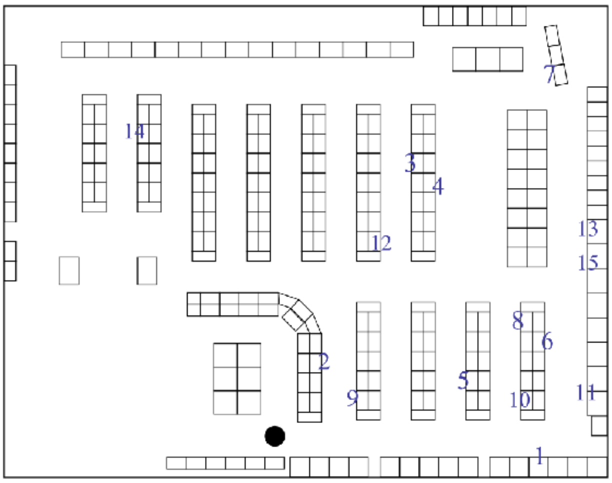

Figure 1: Layout of the original supermarket environment and the location of the fifteen experimental items. The explanations for the numbers (which also represent their order in the search task) can be found in table 1. The black circle represents the starting point. Measurements are: length = 30.8m, width = 24m.

Our initial studies using an existing real store were designed to probe for the influence of background knowledge on humans' (Kalff & Strube, 2009) and robots' (Joho, Senk & Burgard, 2009) navigation decisions. Results regarding the data of 52 human participants are highly indicative of the leverage of knowledge about typical spatial arrangements. Objects that are placed in the proximity of semantically related items yielded significantly lower search times than items violating common spatial (and semantic) proximity relations. Violation means that these items were grouped together with other items the average (and untrained) visitor thought to be inappropriate. Within this last group we further divide the items into two categories: Items that violate strong expectations and items that have many potential neighborhoods. For example, cereal bars, which are expected to be in the vicinity of candy bars, chocolate and sweets are to be found with cereals and oatmeal (which, again, are in a different meso-category, namely "breakfast items") in this particular store. They are therefore in the group encompassing clearly mis-grouped items. We thus conclude that the congruence of items' categorical membership and their real-world contextual embeddedness exerts an influence on navigation.

The results from the real world experiment were subsequently backed up by a replication study in a virtual version of the same supermarket (Kalff & Strube, in preparation). This initial online experiment also serves as a stepping stone for the two variations that are being reported in this paper.

Man-made environments rarely confront their users with oblique angles. Studies have shown that obliqueness causes navigational difficulties (Thorndyke & Hayes-Roth, 1982; Meilinger, 2005) and also affects post-experimental drawings, e.g. the mental representations of street networks (Lynch, 1960). And once perpendicularity is violated, humans show a tendency to mentally straighten angles (Evans, 1980). Our goal in this study is to systematically vary a key spatial property of a realistic building setting while maintaining the majority of other features, like landmarks, thematic proximity of objects, et cetera. For this study we created two oblique versions of an originally highly perpendicular medium-sized German supermarket. This was achieved by rotating each shelf clockwise plus or minus 45° around its geometrical center (see figure 2). Turning the shelves provides a highly controlled, simple means for changing the length and number of key vistas in the setting.

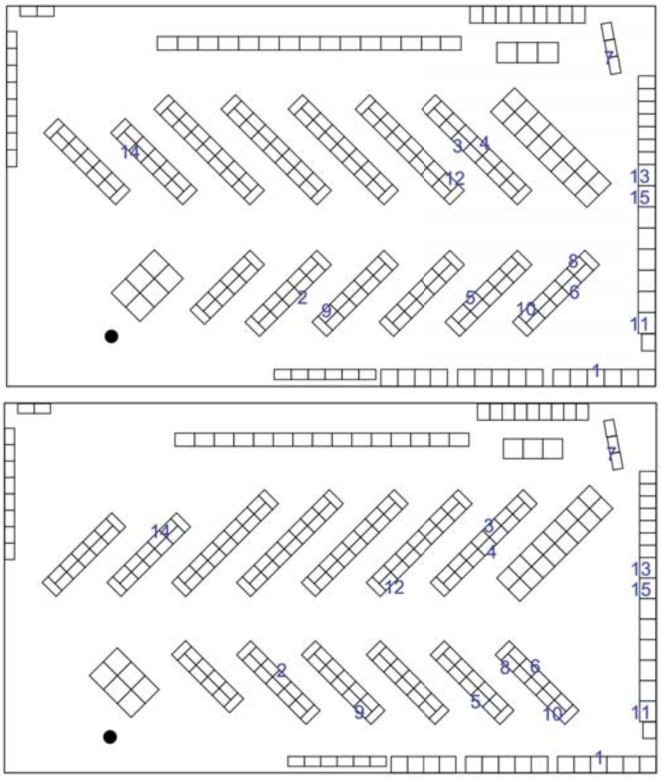

Figure. 2. The two experimental supermarket layouts. The “minus 45°” version on the top and the “plus 45°” version on the bottom. The explanations for the numbers (which also represent their order in the search task) can be found in table 1. The black circles represent the starting points of the active navigation. None of the experimental items were moved during the reconfiguration process and it was strictly controlled for that the disassembly of the shelves didn’t affect background knowledge related processes.

A screenshot of the virtual supermarket, presenting a typical impression of the rotated shelves, can be found in figure 3.

Figure 3. Screenshot of the plus 45° condition of the rotated virtual supermarket. It was taken in the vicinity of item number 4 'salt' and shows the main aisle when looking to the left after having slightly stepped away from the shelf displaying salt, sauces, oil and spices.

A second well-established methodology of spatial cognition research we want to incorporate in our study is space syntax (Hillier & Hanson, 1984). Visual access—to use the term Weisman (1981) coined—was identified as one of the key components of humans' interactions with their environment. And as Gärling, Lindberg and Mäntylä (1983) pointed out, visual access has a substantial impact on wayfinding performance. If large parts of the building are immediately visible and mutual inter-visibility (vistas) connects different parts of the building, people have to rely less on stored spatial knowledge but can use information that is directly available through vision. While aforementioned researchers used intuitive and subjective measurements of visual accessibility, there have also been more formal approaches. Benedikt (1979), for example, evaluated scales of visual access through his notion of 'isovists'. Another methodology for analysing visual access emerging nearly at the same time was space syntax (Hillier & Hanson, 1984). Space syntax is based on different variations of graph analysis and therefore allows researchers to formally "parse" (architectural) space. For both isovist analyses as well as space syntax findings good correspondences have been found regarding psychological measurements of environmental perception (Stamps, 2002) and actual (pedestrian) movement patterns (cf. Hillier et al., 1993; Peponis, Zimring & Choi., 1990; Haq & Zimring, 2003). Across a number of studies, different aspects of wayfinding and navigation have successfully been researched using graph or isovist analyses, e.g. Hölscher and Brösamle (2007) concerning navigation in multi-level buildings or Wiener et al. (2007) on navigation behavior in different architectural settings. Conroy-Dalton (2001) also analyzed the influence of angles at route decision points.

As we have two partially opposing versions of an indoor environment, space syntax is an ideal tool to analyze parameters that are affected by our reconfiguration and might therefore also affect building user's navigation performance. Another strand of space syntax research deals with consumer behavior related issues. Gil et al. (2009), for instance, identified different shopper typologies and their respective shopping paths in a supermarket environment. Even though we are also using a grocery store environment, our sole goal is to investigate issues of (virtual) building reconfiguration and the influence of background knowledge on humans' navigational decisions and not commercial in-store search strategies (e.g. Titus & Everett, 1996).

2 Method

Setting. Two oblique versions of an originally highly perpendicular medium-sized German supermarket were created by rotating each shelf clockwise plus or minus 45° around its geometrical center (see figure 2). A rearrangement that was performed for both versions of the rotated store consisted of disassembling the long produce section shelf to the right of the starting point (cf. figure 1). This resulted in an additional shorter shelf being inserted between the broader and lower produce shelves to the right of the starting point and the cereal shelf hosting item number two (cf. figure 2), so that all tall shelves are uniformly rotated in the store. Then all shelves were moved in such a way that the main aisle (which is the horizontal aisle in the very center of the layout) had an identical width in both conditions. The smaller aisles in-between the shelves (which we term 'shelf aisles') were also made identical with respect to their width and are consistent with the dimensions of the original store. This meant slightly changing the global properties of the two store versions: The length had to be increased for the rotated shelves and their aisle widths to fit. At the same time the width had to be decreased so that the aisles would not become too wide. Due to these changes the 'wine section' shelves on the upper-left side of the store and two sub-shelves of the frozen food department on the upper-right portion had to be moved slightly. As they have no bearing on the experimental items we do not expect effects on the search processes. Performing this reconfiguration led to the plus 45° store being slightly longer than the minus 45° store ($length_{PLUS}$ = 39.8m, $length_{MINUS}$ = 38.3m, both have width = 22.5m).

Participants. A total of 41 people (24 women) aged 20 to 35 years (M = 22.9; SD = 2.84) participated in the study. They were mainly psychology students from the University of Freiburg who either received course credit or a monetary compensation for their participation.

Procedure. Just as with our previous supermarket experiments participants were first briefed on the course of events. A subsequent self-report questionnaire (Münzer & Hölscher, submitted) assessed participants' navigational abilities. After a brief training with the navigation controls in a separate virtual building the main search task was initiated. After completion a series of post-tests were applied. To gauge biases in survey knowledge participants were either given a Euclidean distance estimation task or a triple-comparison of item locations task. A test in the same vein asked participants to render the interior of the store in a semi-structured sketch map and subsequently pinpoint the 15 item locations. A final questionnaire evaluates participants' prior exposure to the specific store, stores of the same chain and more general shopping behavior data. This data will be used to identify the influence of prior experience.

Main search task. The main search task consists of finding 15 different items (at different locations within the store). All items are regular supermarket goods that were not relocated by the experimenters. Instead, with the help of a pre-experimental card sorting task we determined three groups of items out of a reduced selection of 98 grocery goods with differences regarding their background knowledge congruency.

Group 'A' includes items that adhere to the common categorical knowledge of related grocery items with respect to their in-store placement. Furthermore there was high conformity between naïve participants and supermarket managers. Thus, we termed these items "congruent". Group 'B' contains items that appear to be "incongruent" i.e. even though participants highly agreed on semantic relatedness these items are grouped together with other items in the store. The third group, 'C', is termed "ambiguous" because for both participants and store managers there is equivocality regarding item neighbors, respectively suitable in-store placements. Each group comprises 5 items each. An overview of the items and their group membership is shown in Table 1.

Table 1. Order and group membership of the experimental items. See figure 2 for the location of the respective items.

Order	Item	Category membership	Order	Item	Category membership
1	Yoghurt drinks	A	9	Packaged marble cake	B
2	Cereal bars	B	10	Tomato puree	C
3	Tinned maize	A	11	Vanilla yoghurt	B
4	Salt	C	12	Gravy powder	A
5	Cake decoration	A	13	Pickled herring	B
6	Deli olive oil	B	14	Baby food	C
7	UHT-milk	C	15	Fresh yeast	C
8	Long-grain rice	A			

The items had to be searched for in a fixed order. Every found item served as a starting point for the next trial. The starting point for both layout-conditions is located at the left hand side of the supermarket just next to the wall in the middle of the main aisle looking towards the opposite side of the supermarket. Participants remained at that spot for 10 seconds before being passively navigated below the thicker first shelf in the lower half of the store to begin their active search trials. There was a 480 second time-limit for each trial. If participants exceeded this limit they were led to the respective location on the shortest possible path by verbal instructions. At the end of each trial the participants were asked if they had seen the respective item during previous trials. If affirmed, that item would be removed from further analyses.

3 Behavioral Results

Main search task. Before any calculations were performed we excluded those trials where the item had already been seen beforehand. This left us with 567 valid trials from the original 604. The first step in the analysis was to eliminate the influence of the different minimum route lengths (optimal paths) of the trials. A second set of influencing factors we want to eliminate from the raw search time is participants' (differing) knowledge of this particular environment and the frequency of purchase of the experimental items. This was achieved by conducting a two-stepped linear regression and using its unstandardized residuals in the successional analyses. Table 2 shows the respective covariates and their influence on raw search time.

Table 2. The covariates partialed out of the raw search time in the block-wise multiple linear regression. (Note: n. s. = non-significant, * = p < .05, *** = p < .001).

	B	SE B	β	R^2
Step 1				.0001 (n.s.)
Constant	140.36	15.188		
Route distance	0.002	0.007	0.012 (n.s.)	
Step 2				.032***
Constant	148.27	6.174		
Purchase frequency	-21.62	5.802	-.156***	
Total store visits	-.274	.117	-.089*	

Even though the minimal route distance between the items was a non-significant predictor we wanted to remove it from search time to achieve a maximally unbiased measure of the influence of background knowledge. Since the second linear regression step was performed as a backwards regression, only significant predictors are listed for that model in Table 2. 'Purchase frequency' refers to the self-reported frequency of purchase for the 15 experimental items on a five-point scale which was subsequently z-standardized. 'Total store visits' gauges the absolute number of visits to this particular store by the participants[1].The residual of this multiple linear regression will be called 'residualized search time' in the following. Due to some missing covariate data the residualization leaves us with 551 valid trials.

Using the residualized search time as a dependent variable yields the following results. An analysis of variance (ANOVA) with participants as a random factor reveals a main effect of background knowledge category ($F(2, 81.892) = 28.378$, $p < .001$, partial-$\eta^2 = .409$): Items in group 'A' are found significantly faster than in groups 'B' and 'C' (both Bonferroni-corrected post-hoc comparisons $p < .001$). With the participants being faster in the minus 45° condition (M = -14.642, SE = 7.78)[2] than in the plus 45° condition (M = 6.73, SE = 7.35) there is also a main effect of condition ($F(1, 539) = 3.98$, $p < .05$, partial-$\eta^2 = .007$) but no interaction of category and condition ($F < 1$). A final main effect is found for gender with men (M = -16.743, SE = 8.1) outperforming the women (M = 8.83, SE = 7.01) ($F(1, 539) = 5.699$, $p < .05$, partial-$\eta^2 = .017$), most likely due to greater familiarity with video game interfaces (see Kalff & Strube, in prep.). All other interactions clearly miss significance. Thus, these results parallel our previous findings on the influence of background knowledge on navigation performance. But most importantly they indicate substantial differences between the two variations of the shelf configurations.

A more detailed impression can be gained if we look at the comparison of the two conditions at the individual item level. This will also allow for the incorporation of

[1] This variable proved to explain more variance than the 'weekly visits to this particular store' variable.

[2] Negative values are due to linear regression standardization process during which the initial mean value of the dependent variable is set to zero. This will therefore lead to the grand mean being zero in all the ANOVA procedures.

space syntax measures which will be reported after the behavioral results (section 4). This analysis confirms the effects regarding condition and gender. Other than that, there is only a main effect of items: $F(14, 491) = 6.648$, $p < .001$, partial-$\eta^2 = .159$. All other interactions clearly miss significance (all Fs < 1). Even though the item and condition interaction lacks overall significance a look at the individual items (see figure 4) reveals that the search time differences are most prominent for ‘tinned maize’, ‘vanilla yoghurt’ and ‘tomato puree’. In fact, if no measures are taken to control for multiple testing the difference for ‘vanilla yoghurt’ is significant ($p < .05$) and we observe marginal significance for ‘canned corn (also named tinned maize)’ ($p = .074$).

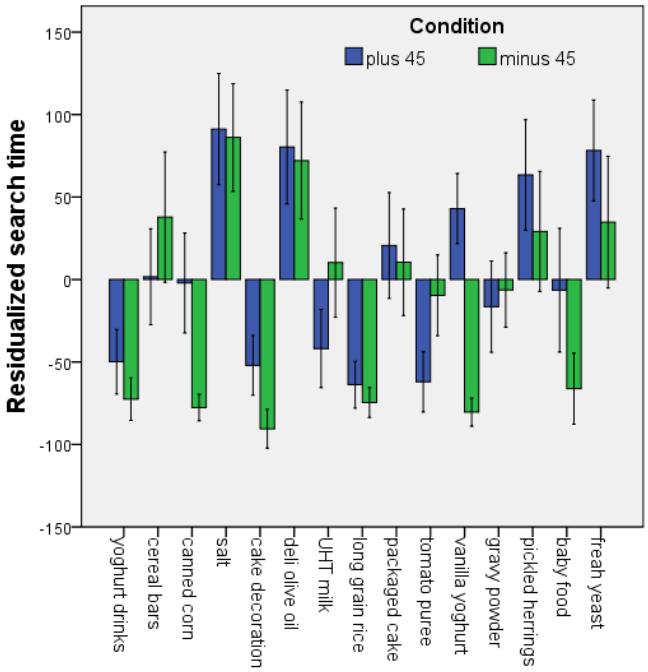

Figure 4. Mean residualized search time over items and experimental condition. Error bars depict one standard error of the mean.

Table 3 is designed to summarize the behavioral results. It will also include the post-test results which will be reported in the following. The ‘Direction’ column will explicitly show how the factors are influencing the dependent measures.

Table 3. Overview on the behavioral results. (Note: n. s. = non-significant, * = p < .05, *** = p < .001, the '<' symbol represents superior performances [lower residualized search times/ more accurate drawings]).

Dependent variable	Factor	Significance	Direction
Residualized search time	category	***	'A' < 'B' & 'C'
	condition	*	'minus' < 'plus'
	gender	*	'men' < 'women'
	items	***	cf. figure 4
	all interactions	n.s.	-
Turning of drawn shelves	condition	n.s.	-
	gender	*	'men' < 'women'
Number of drawn shelves	condition	n.s.	-
	gender	n.s.	-
Individual item markings	items	***	-
	condition	n.s.	-
	items*condition	n.s.	-

Drawings. The post-experimental drawings are evaluated by three measures. First, we assessed if the shelves were turned at all (with the turning angle not necessarily equating the exact 45°) and if they were turned in the right direction. Thus, this resulted in a coarse binary 'right/wrong' measure. Second, the number of drawn-in shelves was counted. The third variable was assessed by measuring the deviations of participants' item markings and the correct locations.

A comparison of the 'correct shelf turning', condition, and gender variables only shows significant differences for gender: Women's (15 errors out of 24) mental representations are significantly poorer than men's (4 errors out of 17): $\chi^2(1) = 6.078$, $p = .025$, $\Phi = .385$. Regarding the number of shelves, participants tend to underestimate their true amount; the mean being -3.1 (SD = 1.99; Med = -3). The difference between the two conditions is marginally significant: the ANOVA shows that the minus 45° condition (M = -2.47, SE = .44) is superior to the renderings of the plus 45° condition (M = -3.58, SE = .43): $F(1, 37) = 3.267$, $p = .079$, partial-$\eta^2 = .081$. All other F-values are smaller than 1.

Finally, the marking of the individual items reveals the following results (due to a violation of sphericity ($\chi^2(104) = 156.27$, $p < .001$, $\varepsilon = .544$) the Huynh-Feldt correction will be used). The repeated-measures ANOVA shows a marginally significant interaction of items and condition: F(12.318, 320.262 = 1.638, p = .078, partial-$\eta^2 = .059$) and a significant main effect of items: $F(12.318, 320.262) = 4.773$, $p < .001$, partial-$\eta^2 = .155$. Even though item marking accuracy was higher for the minus 45° condition (M = 37.32mm, SE = 4.7) than for the plus 45° condition (M = 46.89mm, SE = 4.7) this difference is not significant ($F(1, 26) = 2.067$, $p = .162$, partial-η^2 = .074). But again, in summary, one can conclude that the minus 45° condition produced better renderings of the store environment and by trend led to more accurate item markings.

Correlational aspects. Taking all participants into account the following correlations are found. Drawing accuracy correlates highly with search time performance ($r(39) = .549$, $p < .001$). Search time is also marginally significantly correlated with the number of shelves participants missed drawing ($r(40) = -.307$, $p = .054$), i.e. the faster participants completed the search task the better were their renderings of the store's interior. There are no correlations of experimental performance and the three scores derived from the pre-test questionnaire designed by Münzer and Hölscher (submitted).

Preliminary result. Summarizing the behavioral results leads to the conclusion that the minus 45° condition was easier for the participants, both with respect to navigability and the creation of beneficial survey knowledge. One explanation we can offer at this point has to do with the first exposure participants received of the store. Before being led to the starting point the ten second information gain regarding the different product categories and their possible ordering is much higher in the minus 45° condition. Of course one could argue that participants in the plus 45° condition merely have to traverse the main aisle once to receive a similarly rich perspective.

The original store. We want to briefly compare these results with those we determined in the original or perpendicular store (cf. fig. 1) before we head to the space syntax analyses. Regarding the effect of background knowledge congruency, there are main effects of category and (marginally significant) for condition with the perpendicular or normal version ranging between the rotated ones. And there is a marginally significant interaction of category and condition. This is due to lower search times for the incongruently placed items in the original store configuration. The gender effect of men outperforming women also remains stable. At the individual item level there is a significant interaction of items and condition, because of the significant difference for deli olive oil between the unrotated and the minus 45° degrees condition - latter yielding lower search times.

The strongest result concerns the post-experimental drawings. When comparing the unrotated virtual store with the (aggregation of the) two rotated versions drawing performance decreases drastically ($M_{ORIGINAL}$ = 25.04mm, SE = 3.92; $M_{ROTATED}$ = 42.1, SE = 3.272): $F(1, 47) = 11.177$, $p < .002$, partial-η^2 = .192. A full account of the comparison between the original store and the layout variations will be reported in a future publication.

4 Space Syntax analyses

At this point the question arises, if and how visual access plays a role for the effects we found. To answer these questions we use space syntax analysis to compare the two different layouts. To begin with, we evaluate a selection of global measures of the two store layouts. These include intelligibility, average integration, and average connectivity. From the wide range of analyses that space syntax offers we additionally performed the following: To check up on the postulated information gain difference at the exposure point a simple vista space evaluation will be performed as an isovist analysis. More elaborate analyses will consider the classical notions of intelligibility, integration and the different values of isovists and step depths. One further ad-hoc analysis we think is of great usefulness concerns the role of the main aisle. Not only are participants aware of its existence from their very first exposure of the virtual store, but we postulate that participants will preferentially resort to it, when navigating through the store. This should hold true especially when they have no clear-cut idea where the items' (alleged) corresponding categories are. We therefore want to take into account how visible the main aisle is from every experimental item. In this paper, our source of an isovist is the target product itself, because we feel that in a complex environment like a supermarket it would be most useful to have a product that is visible from a great area. We propose to call such isovists of target products – *product-catchment-areas*.

However, the first stage of analysis deals with the global comparison of the two store versions. This will include intelligibility, average integration and average connectivity. All space syntax analyses were performed with the Depthmap software (Turner, 2004). Some areas of the store were purposefully blacked out before running the analyses. This includes a rectangular section in the lower-left corner that was never exploited by the participants. We also sealed off the gaps between the wall shelves, because they were not accessible for the participants.

Global analysis. Table 4 shows the global properties of the two supermarket versions. As the numbers reveal, there are virtually no differences in the global geometrical properties of the two versions which could explain the significantly superior search time performance in the minus 45° condition.

Table 4. Global properties of the two store configurations.

	Intelligibility[3]	Integration (HH[4])	Connectivity
Plus 45°	0.8043	10.1394	1418.9471
Minus 45°	0.8715	10.2636	1380.7819

Since intelligibility is defined by the correlation between connectivity (i.e. the amount of neighbors a location is visibly connected to) and integration (which basically represents the amount of steps it takes to get from one particular location to any other in the environment) it provides information about how much the local structure allows for predicting the global structure. High intelligibility is the case for both layouts. The similarities between the two layouts are also corroborated when looking at the two visibility graph analyses (VGA; Turner, 2004) depicted in figure 5. The color ranges from red – representing highly integrated parts of the supermarket –

[3] Values show R^2-values of the linear regression as a result of the scatter plot for Integration times Connectivity.

[4] This is the Integration algorithm described by Hillier and Hanson (1984).

to dark blue, the least integrated areas. As can be noted the main aisle is the most integrated part of the environment in both conditions. Thus, no substantial environmental differences have been determined hitherto. We will therefore move to a more detailed comparison.

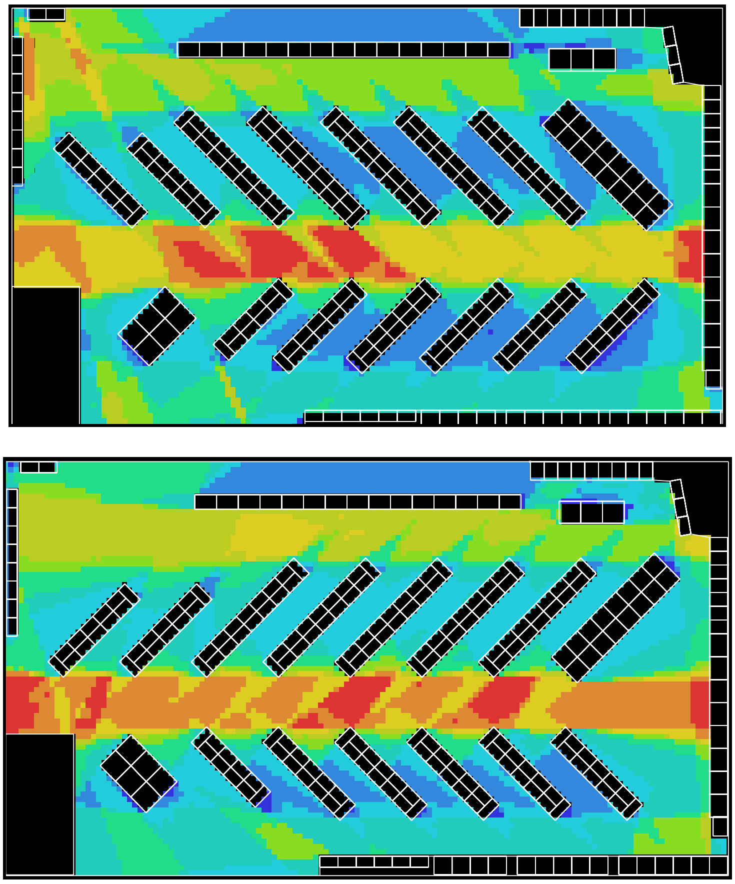

Figure 5. Visibility Graph Analyses (VGA) using the Hillier and Hanson (1984) Integration version. The minus 45° condition on top and the plus 45° on the bottom. The black rectangle in the lower left corner is used to exclude this area from the analyses. This was done because (even though not explicitly blocked during navigation) participants never used this portion of the store and there are no grocery goods there.

Individual item analyses. Individual item analyses were performed for every item as a 'product-catchment-area' considering all isovist measures and integration. Additionally, we analyzed the route between each starting point and its target location. We evaluated a total of 14 space syntax measures for each item (product) and condition (plus 45° / minus 45°):

- The percentage of the main aisle that is visible from every ‘product catchment-area’.
- Visual step depth which is based on the amount of visual turns that need to be made between starting point and target location (c.f. Turner, 2004). This provides useful information about the number of decisions people will have to make to reach a destination point.
- Metric step depth weights those visual steps with their metric length.
- Shortest angular path and angular step depth: these measurements are especially interesting, since the shelves’ rotation is the only actively induced modification compared to the original layout and leads to differing shortest paths between the conditions.
- Isovist area gauges the influence of the area a product is directly visible from in the supermarket.
- Isovist compactness: the ‘roundness’ of an isovist will be of interest for the difference between items that are located at the far ends of the market, where compactness is rather high versus the items between two shelves and even more so for the ones on aisles near the outer walls of the super market (called ‘side aisles’ in the following). In those latter cases compactness is rather low.
- Isovist drift angle and isovist drift magnitude: these provide information about the influence of asymmetry on visual access for target products.
- The minimum and maximum radial of the isovists as well as isovist perimeter. Especially for perimeter a high value increases the probability of this point to be seen from many different vista points.
- Isovist occlusivity: this accounts for parts of the isovist perimeter that are occluded but permeable, and therefore, participants can pass those areas to gain visual access to the products.

A multiple ANOVA was conducted across all products and conditions ($N = 15 * 2 = 30$), with the space syntax variables as *dependent* measures. We obtained no significant differences between the two conditions regarding all these variables.

The next step of the analysis is to relate the environmental variables identified in this section to behavioral data, i.e. search performance in the supermarket. This will address the open question, what makes the minus 45° condition significantly easier for human participants. For this purpose we now include space syntax variables in a standardization process for obtaining a further refined residualized search time. The following analysis will thus test to what extent the (albeit small) differences in the space syntax measures can explain some of the variance leading to the performance differences between layout conditions.

Re-analysis with space syntax measures. For this purpose another backward linear regression with the residualized search time as a dependent variable and the above mentioned variables as predictors will be performed (see Table 5). Multicollinearity is controlled for by examining the Variance Inflation Factors of the predictors (all VIF’s in the model ≈ 1).

Table 5. The space syntax variables partialed out of the residualized search time in the stepwise multiple linear regression. (Note: * = p < .05, ** = p < .01, *** = p < .001).

	B	SE B	β
Constant	-95.64	14.52	
Area of main aisle	112.51	25.49	.190***
Isovist compactness	309.14	47.57	.280**

R^2 = .081, F(2, 548) = 24.268, p < .001.

Two of the space syntax measures are able to account for additional variance. A detailed look at the particular predictors explains their raison d'être. The area of main aisle visible from every item increasing search time appears counter-intuitive at first glance. But one has to keep in mind, that search in such a semantically dense environment as a supermarket is not (solely) guided by geometrical realities but by categorical dependencies, and therefore, more visual input which can be equated to more and possibly confusing product categories that increase search time. The significant influence of isovist compactness on the other hand shows that long lines of sight through the whole store nevertheless are beneficial since the lower the isovist compactness (and therefore the bigger the difference between maximum radial and average radial) the quicker participants find their way to the product. This also means that in areas where an isovist's shape is more compact than, for example, in-between shelves, search times are rather high. In our study, round isovists are found at the sides of the supermarket which are areas where people do not tend to go since most products are visible from the middle of the store and therefore the main aisle.

Repeating the ANOVA procedures on the behavioral results section after the space syntax measures have been partialed out shows that even though the results regarding the background knowledge congruity still yield significance (F(2, 81.554) = 8.306, p < .01) their impact has dropped (partial-η^2 = .169; compared to partial-η^2 = .409 in the previous analysis, see section 3, 'main search task'). Regarding the most prominent question of differences between the two conditions, the additional considerations of environmental properties yields the following picture: The minus condition (M = -13, SE = 7.57) is no longer significantly easier than the plus condition (M = 4.85, SE = 7.12): F(1, 539) = 6.87, p = .096, partial-η^2 = .005. And again there is no interaction of items and condition: F(14, 491) = 1.226, p = .252.

As reassuring as these results are for gauging the influence of pertinent background knowledge on navigational decisions and performance, they also shed light on the difference between the two shelf configurations. After taking the space syntax measures into account, there is no longer a significant performance difference between the two, i.e., the space syntax measures indeed capture relevant variance underlying the performance difference. Yet, it still has to be identified how exactly the space syntax measures differ between the layouts. To dig into the matter we want to have a look at the two conditions separately. Perhaps they don't share the same predicting variables and exhibit different correlational properties. For this purpose Table 6 contrasts the correlation of the residualized search time and the space syntax measures. The last column reports the significance value of the difference in correlations computed via Fishers Z-transformation, i.e. if the strength of correlation differs significantly between the two conditions.

As the last column shows, there are indeed differences in the correlations of environmental features and participants' search times between the two conditions. Area of main aisle, isovist drift magnitude and the isovist's minimum radial show significant differences. Of these variables, though, only area of main aisle has proven to be a significant predictor for search time and therefore we focus on it in the following analysis. While a higher value lowers search times (though not significantly) in the minus condition, the plus condition's items worsen with increasing visibility from the main aisle. A factor analysis performed on the abovementioned 14 space syntax variables sheds some light on the fact that area of main aisle is a significant predictor in the regression (see table 5) despite being non-significant in table 6 here. This is due to it sharing variance with other (significant) variables like isovist area, isovist maximum radial and integration in the factor analysis.

Table 6. Correlations of residualized search time and space syntax measures for the overall case and the two conditions individually (n = 290 for plus and n = 261 for minus). (Note: ^{M} = p < .1, * = p < .05, ** = p < .01, *** = p < .001).

	Overall	Minus 45° condition	Plus 45° condition	p-value of significance of difference
Area of main aisle	.103	-.010	.165**	p = .039*
Visual step depth	.183**	.168*	.195***	p = .745
Metric step depth	-.046	-.065	-.031	p = .691
Angular step depth	.217***	.229***	.222***	p = .931
Shortest angular path	.192***	.170**	.206***	p = .664
Isovist area	.085*	.014	.140**	p = .139
Isovist compactness	.221***	.208**	.238***	p = .713
Isovist drift angle	-.008	-.070	.022	p = .283
Isovist drift magnitude	-.035	-.140*	.062	p = .018*
Isovist max. radial	-.019	-.098	.056	p = .072^{M}
Isovist min. radial	.098*	.005	.194**	p = .026*
Isovist occlusivity	-.078^{M}	-.084	-.071	p = .87
Isovist perimeter	-.028	-.042	-0.10	p = .497
Integration	-.008	-.081	.047	p = .691

The second most influential factor contains isovist compactness and the significant variables angular step depth and shortest angular path. We suppose that low compactness that is due to an isovist comprising big areas, especially along the main aisle and side aisles, is naturally correlated with lower step depth and particularly angular step depth. If one is in any of these aisles less steps and less turns are needed. Thus, the two predictors in table 5 are representative of the two strongest factors of the factor analysis.

Because the area of main aisle (visible from every item) yields a significant difference between the two conditions, we are convinced that this stems from participants using it in a different manner. Perhaps the shelf configurations "lead" participants either away or towards the main aisle, which is probably dependent on the location within the aisle. And of course, one always has to bear in mind that there may not only be differences between the two conditions but between the three background knowledge congruency groups as well. Thus, participants may not have adhered to a single strategy, but switched depending on their metaknowledge of product categories. We want to tackle these questions in the following.

Main aisle analysis. As the area of main aisle that is visible from the products is a significant predictor for the plus 45°-condition only, we first want to examine how much time participants spent on the main aisle. The data was obtained by computing gate counts from the trajectory data. Therefore, we subdivided the supermarket into different areas along the axis orthogonal to the supermarket's main axis. We defined one area for the middle aisle, two areas tangent to that area covering all the shelves and two areas covering the aisles at the two long outer walls of the supermarket. The lengths of the areas were the same as that of the supermarket and the breadths were chosen so as to cover the stated areas. We then counted how long our test subjects remained near the outer walls, in the main aisle or in one of the two shelf aisles.

Again, to rid the data of the varying experience of participants with this particular store a stepwise linear regression with the data from the covariate questionnaire will be performed.

Table 7. The covariates partialed out the time participants spent in the main aisle. (Note: *** = $p < .001$).

	B	SE B	β
Constant	712.52	32.25	
Item purchase frequency	-116.44	33.56	-.146***

$R^2 = .021$, $F(1, 550) = 12.035$, $p < .001$.

As can be seen in table 7 the only significant predictor is the z-standardized item purchase frequency. The unstandardized residuals of the regression are then analyzed using an ANOVA taking the same factors into account that were also used for the main search time evaluation. The ANOVA shows a significant difference between the two conditions ($F(1, 554) = 3.874$, $p < .05$, partial-$\eta^2 = .007$): Participants spent more time in the main aisle in the plus condition ($M = 48.42$, $SE = 44.13$) than in the minus condition ($M = -76.612$, $SE = 45.68$). Of the other factors, both gender ($F(1, 554) = 6.46$, $p < .05$) and category ($F(2, 554) = 16.18$, $p < .001$) are significant with the same trend as for the search time analysis performed above. None of the interactions reach significance.

To examine this differing usage of the main aisle we want to report an exemplary qualitative analysis in the following.

5 Qualitative Analysis

As our goal is to determine the differences between the two experimental conditions, we want to examine more closely how the turning of the shelves and background related processes interact. This will be done in a qualitative fashion using participants' actual trajectories and breaking down their behavior and decisions in a step-by-step fashion. This is achieved by iterating through the following set of questions:

- Which choices might be encountered on an ideal search-path between starting point und target product?
- When does background knowledge prove to help or indeed make it more difficult for participants to find a certain target product?
- Are there indications that argue for the interaction between the use of background knowledge and visually-driven search strategies? What does this interaction look like?

We want to point out that the further analyses are qualitative and rather standing at the beginning of further research. As such, we are using examples of research elements that make it possible to figure out different strategies in detail. The goal is to try and understand strategies and heuristics for path choices in this particular environment by looking at the decisions made. Those decisions are reconstructed through interpretations of trajectories and thinking aloud protocols. We are giving one example to show the working process. Item and layout can be seen in figure 6: The task was to find the tinned maize.

We begin with analyzing the different layouts. Asterisks account for starting points, circles for target-product locations. We use numbers at points on a route to alleviate following the description. In both conditions the ideal path (as marked with continuous lines) would be: Firstly, choosing to walk along the main aisle and from there, secondly, in the direction of tinned maize. Then, thirdly, turn away from the main aisle at the appropriate junction. The next step will be looking at visual guiding principles and the influence of background knowledge separately for both conditions.

The plus 45° condition. Looking at the „plus" condition (see figure 6): Due to the rotation of shelves the main aisle is close and easy to reach from the departure point (marked by the asterisk), which is why one can assume preferences for the main aisle direction (c.f. Gärling, Säisä, Böök, & Lindberg, 1986). From that point, there is the possibility to go to the non-food section on the left or the food section on the right side of the supermarket (tagged with 'p1' in the figure). Although the rotation angle is bigger for the food section (one prominent strategy is to try minimizing the rotation angle at decision points, as worked out in Conroy-Dalton, 2001) background knowledge will presumably lead to the right side. Being on the main aisle heading for the food section participants face the difficulty of shelves being turned away from the main aisle so that products cannot be recognized easily without actually walking through the aisles between two shelves. Therefore it should be more difficult to decide on the appropriate path (see tag 'p2').

Still with respect to the plus 45°-condition, starting once more at the very first decision point (the asterisk), participants choosing their path to the lower side aisle will face quite different situations (see the dashed line). The shelves are rotated into the direction of the food section in the back of the supermarket. The integration of background knowledge and rotation of the shelves favor the way to the front end of the supermarket ('p3'), following the lower side aisle. In this aisle, parts of the shelves and therefore products and categories are clearly visible which makes it easy to see if there is a product that is similar to or even matches the one participants are searching for. However, participants need to make a rather big turn (more than 90°) if deciding to walk along one particular shelf. Since there are no obvious triggers for background knowledge until the last shelf in the row this increases the probability of walking along the lower side aisle until ‘p4’. In addition, when we looked at the trajectories we noticed quite a few participants searching for the target in this last shelf at the front end of the supermarket (see figure 7).

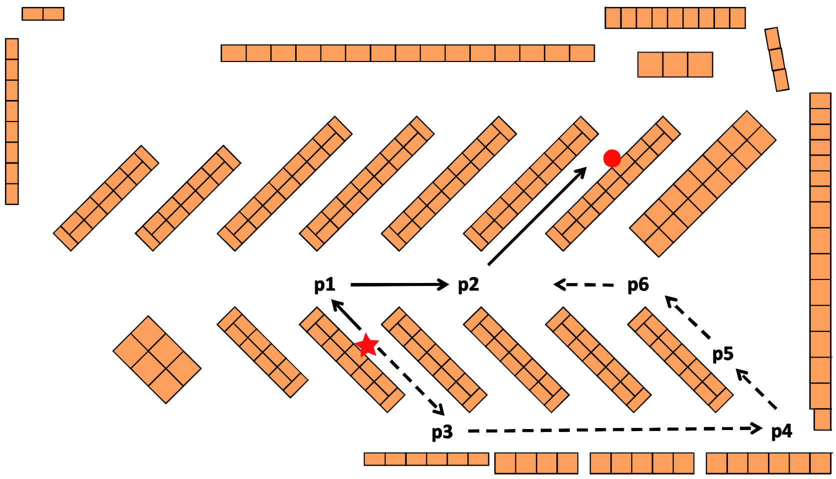

Figure 6. Departure point and target location for the experimental item ‘tinned maize’ in the plus 45° condition. The starting point (‘cereal bars’) is marked by the asterisk, maize is depicted through the circle. The ideal path is indicated by the continuous lines; alternative routes are marked with dashed lines. ‘p1’ to ‘p6’ denote decision points that we are focusing on.

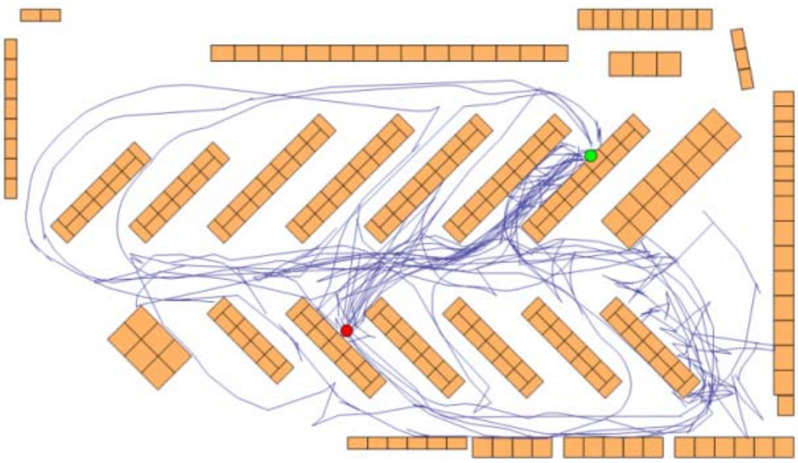

Figure 7. Aggregated trajectories of participants searching for tinned maize in the plus 45° condition.

This is a shelf with delicatessen, including tins and jars. Those tins and jars probably trigger a packing heuristic: Thus, the shelf forms a distractor. This is backed by statements in thinking aloud protocols. Here, many participants communicate from the very beginning that they are searching for tinned food:

> *„… Maiskörner sind bei den Dosensachen…"*
> *„…maize is located near the tinned food…"*

From this point, participants will presumably get lured along the shelf (searching for tinned maize at 'p5') straight into the main aisle ('p6'), where they basically face the same problems as their partners using the main aisle straight away. Additionally, they now fare even worse due to them walking in the opposite direction; i.e. the tinned food is located at a suboptimal angle.

As one can see in figure 7 there is a quite obvious and extended usage of the main aisle. But participants are rather walking back and forth without being able to decide for one shelf or aisle. Only once they reach the back end do they tend to turn and walk through to the upper side aisle, where they stay on and walk until they can see the target product from this direction.

The minus 45° condition. How might people act in the minus-layout? Again, we can assume that participants aim for the food section. This time, shelves are rotated in such a manner that the point of departure is not located near the main aisle, but rather facing the lower side aisle. Accounting for the "searching for food article assumption" we would still expect the preference for following the direction of the shelf into the main aisle. This is because the shelves lead to the food section on their way to the main aisle (see figure 8, tag 'm1'). In contrast, turning 90° to the left and walking on will lead you to the back of the supermarket which is the non-food section ('m4'). Moreover, the departure point is rather located in the back. Finally, we believe that the main aisle is part of a hierarchical strategy: if participants do not yet have a complete picture of the location of different product categories around the supermarket but do have semantic background knowledge about the target product and its semantic neighbors, the simplest way to find the product is to go where you can overlook the biggest part of the supermarket – the main aisle. This hypothesis is backed by several comments derived from thinking-aloud protocols where we found statements like the following:

> *„… geh ich mal wieder hier in diesen Mittelgang und versuche mir einen Überblick zu verschaffen…"*
> *„… again I go back here into this middle aisle and try to get an overview…".*

Once in the main aisle ('m1') lower turning angle and background knowledge both favor turning right and going down to the front end. If participants are walking in this direction, the target shelf is facing the main aisle ('m2'). The target product itself is not immediately visible but there are a lot of tins and jars ('m3').

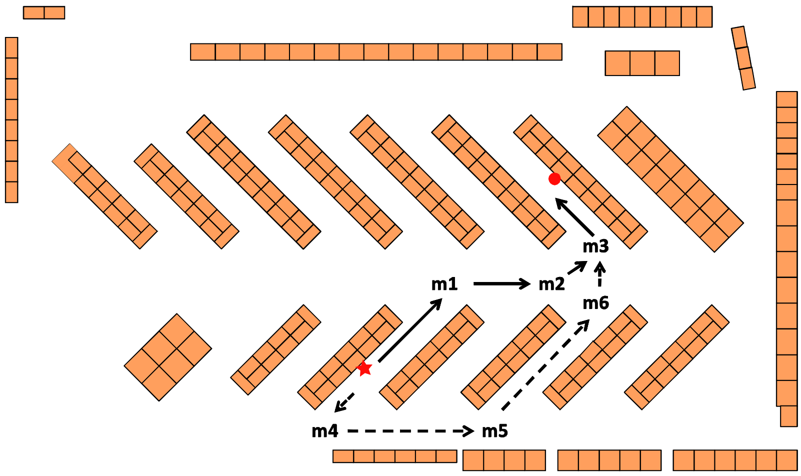

Figure 8. Departure point and target location for the experimental item ‘tinned maize’ in the minus 45° condition. The starting point (‘cereal bars’) is marked by the asterisk, maize is depicted through the circle. The ideal path is indicated by continuous lines; alternative routes are marked with dashed lines. ‘m1’ to ‘m6’ denote decision points that we are focusing on.

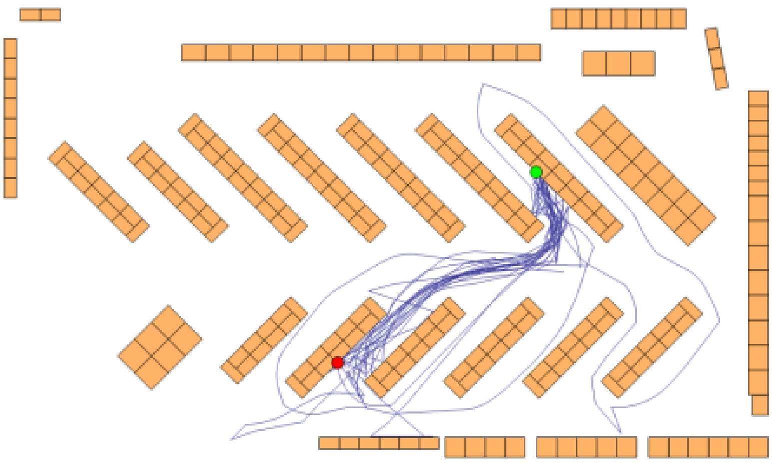

Figure 9. Aggregated trajectories of participants searching for tinned maize in the minus 45° condition.

If participants use the lower side aisle in the beginning (‘m4’), background knowledge about placing of food items on this side might step in again to lead the way to the front end of the supermarket. The shelves’ rotation is turned away from the side aisle. Participants have to walk along between the shelves to see the products (for example turning at ‘m5’). This again guides them to the main aisle (‘m6’), if they don’t want to turn around and walk back to the lower side aisle (which would be of considerable cost regarding time and distance as there are no new products). Again, the trajectories fit very well with those interpretations (see figure 9).

This item search has been a fairly simple task but as you can see even this task shows a very complex structure where visibility and background knowledge are constantly interacting and, moreover, where route decisions can lead to different interactions of both variables. Sometimes strategies like using the main aisle can be very useful—if shelf rotation favors visibility of the target products—but very confusing as well—if shelf orientation doesn't support the visibility of the shelf or even worse if it supports distractors. In fact, things become more difficult by taking into account heuristics like the aforementioned packing heuristic. Participants are most certainly not semantically connecting tinned maize and the delicatessen shelf. But in a complex environment visible bottom-up information ('there are tins in the delicatessen shelf') and top-down information ('maize comes in tins') are flexibly used while encountering products in the layout.

In summary we would like to conclude that reconstructing possible path choice decisions reveals complex interaction between background knowledge and visibility. The heuristic of using the most integrated part of the building—the main aisle—for orientation can be either helpful or irritating depending on the rotation of the shelves. The next step for future research on this aspect is to categorize different forms of interaction and provide a framework of possible rules that can be empirically validated.

6 General discussion and future research

With the help of a virtual version of an existing medium-sized supermarket we designed two new store layouts: All shelves were either rotated plus or minus 45° around their geometrical center. The participants' task was to find 15 items which exhibited different degrees of congruency regarding their in-store placement and the generalized background knowledge average consumers have regarding their semantic neighborhood. The study finds significant differences between the two shelf configurations, as the minus 45° condition was overall easier for the participants. Breaking down this main effect by looking at differences for the individual items doesn't yield any significant interactions, but confirms the superior search performance in the minus 45° configuration. An initial analysis of environmental features with a wide range of space syntax measures shows no major differences between the two conditions, neither for global properties such as overall intelligibility or connectivity, nor for several analyses at the individual item level. Re-analyzing the behavioral data after partialing out the strongest space syntax predictor variables does eliminate the significance of behavioral differences between the two conditions, though. Viz., the space syntax measures that were evaluated capture some of the behavioral and cognitive effects the layout variation has on human's search performance. Namely, the area of main aisle that is visible from the target locations and isovist compactness are significant predictors of search time. Contrasting the strengths of the influence of the different layout properties reveals further differences, as the area of main aisle only has a hampering influence in the plus 45° condition. We thus conclude that the orientation of the shelves seems to function as a guiding appliance that "deflects" building users into different directions and causes the significant difference in occupation of the main aisle throughout the search trials by participants in the two conditions. And, of course, the results reveal the strong coupling of semantically guided navigation decisions and the hard constraints of environmental properties. Geometrical variations between items and layout versions are able to explain variance that in our original study (Kalff & Strube, 2009) was attributed to background knowledge about category placement and category membership of products. At the same time, background knowledge has a significant impact beyond what the space syntax analyses have been able to explain thus far. To successfully untangle the interaction of background knowledge and geometric influences, we need to further refine the analyses on the level of individual products, categories and trajectories. The qualitative analysis of decision making for ‘tinned maize’ in the preceding section is a step towards this goal.

Another aspect we definitely want to tackle is to capture the navigation behavior with the help of an agent simulation. Turner & Penn (2001) and Penn & Turner (2001) have introduced a simulation approach that builds upon the Visibility Graph Analysis method employed in this paper. We have conducted preliminary test with these agents within the Depthmap software. So far, this VGA agent modeling has failed to match the human search pattern in our study. The qualitative analysis in section 5 suggests that this is likely attributable to a lack of modeling background knowledge in these agents. We suspect that at least for parts of the human trajectories observed in this study, the Depthmap agents could provide substantial correspondences. To capture this, we intend to analyze the trajectories of each participant per item in more detail. A promising approach is to translate the continuous space of the store environment into larger segments (roughly corresponding to single aisles) and obtain gate counts at segment boundaries (as detailed in Hölscher, Brösamle & Vrachliotis, in press, for a conference center setting). The relative usage frequency for different items between layout conditions can then be compared to the agent’s behavior.

A similar analysis of correlations between search times and space syntax measures (cf. table 5) will look at differences between the three groups of items (congruent, incongruent, and ambiguous) and how they are differently affected in the two layout conditions. Preliminary analyses suggest that the isovist area in the two layouts, for example, affects incongruent items differently than congruent items: For the congruently placed items of group ‘A’ isovist area shows a negative correlation with search time, i.e. ‘seeing more’ equals ‘finding faster.’ The opposite is true for items of groups ‘B’ and ‘C,’ which have a lot of plausible product-neighborhoods—the higher their visibility the longer they are searched for. And this, again, is more strongly pronounced in the plus 45° condition. It remains an issue of future research to clarify to what extent such differences reflect a true interaction of semantic and spatial features or whether they are better characterized as artefacts of item selection in this particular study.

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JUDGEMENTS OF BUILDING COMPLEXITY & NAVIGABILITY IN VIRTUAL REALITY

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Abstract. This paper presents an experiment on judgments of the perceived complexity of corridor layouts, experienced within a CAVE™-based virtual reality. This work built upon an earlier experiment (Hölscher and Dalton, 2008) in which identical stimuli (the layouts of corridor systems in buildings) were presented in two modes: plan views and movies of simulated walkthroughs. By reproducing the earlier study data has now been gathered for three modes of presentation, the final being a virtual environment. After an initial training level, six randomly ordered stimuli were presented to 20 subjects: 'experts' (architects or students currently enrolled on an architectural course) and 'lay people' (all others). In each of these corridor systems, subjects were instructed to walk from the starting location ('A') to a distant goal ('B'), and to return unaided. Pointing tasks were undertaken at both locations A and B. They were then asked to judge the complexity of the layout and estimate the difficulty or ease of navigating in that environment. Finally they were asked to identify the correct corridor-layout from a series of similar plans. The aims were to investigate whether there were differences between these two groups in terms of their judgments of building complexity, effects of modality of stimuli (as compared to the earlier experiments) and if any environmental measures (for example information theoretic-based) correlated with the assessments of the two groups. The results were, first, that there is a significant effect of modality, and that the CAVE™ appeared to produce far better correlations with environmental measures of complexity (compared to the plan and movie views) and, second, that the differences between the judgments of the experts and non-experts were far less pronounced in this study, compared to the earlier study, possibly due to the limited number of layout-stimuli or to the relative simplicity of the corridor systems.

1. Aims

Understanding the physical parameters that make a building layout 'complex' continues to pose challenges to both architectural theory and empirically based cognitive sciences. Layout complexity has repeatedly been investigated on the basis of subjective ratings of layouts, but with a distinct lack of formalizing the properties of the environment and without taking different presentation modalities into account, i.e. whether such assessment is based on viewing only a plan of a building or, for example, actually experiencing a three-dimensional, immersive view of it.

The aims of this study were, first, to further investigate the role the mode of presentation of the building, building directly upon and re-using data from an earlier study by Hoelscher and Dalton (2008), by extending the earlier two modes (2D, plan view and walkthrough movie view) to encompass a third mode, that of active navigation within a virtual reality simulation. It was initially hypothesized that the act of active navigation in a CAVE™ environment should produce the closest possible experience to navigating in the real world (but within highly controlled test-environments), and therefore should produce quantifiably different results to those found in the earlier study, which utilized far more representative forms of presentation (2D drawings and movies). However, since, in Weisman's original 1981 study (which influenced Hoelscher and Dalton's subsequent 2008 study), he found that judgements of building layout complexity and judgements of potential navigability were related to real-world navigational performance our expectation was the results from the more recent CAVE™ study would similarly reflect the results of the earlier 2008 study.

The second aim, was to investigate whether, in a CAVE™-based simulation, the architects in the study view layout designs differently, with respect to judgements of complexity and/or ease of navigation, hence replicating the finding of the previous study (ibid). Montello recently suggested (2007) that "architects will generally see greater differentiation in the built environment than non–architects", and this was, to some extent, found in the earlier study (see next section). It was hypothesized that similar differences between 'expert' and 'non-expert' subject would be found in the follow-up virtual reality study.

The third aim, was to investigate whether the subjects' ratings of either corridor-layout complexity or of ease of navigability correlated with a series of environmental measures, including geometric measures, visibility-field based measures, configurational (space syntax) measures and a series of information-theoretic measures. Again, a large proportion of these were used in the earlier study and the expectation was that a selection of these measures could usefully serve to predict the subjects' judgements.

2 Method

2.1 BACKGROUND (PREVIOUS EXPERIMENTS)

The study by Weisman (1981) provided the first systematic assessment of floor plan complexity by human judges. He used thirty simplified building layouts that spanned a wide variety of building styles (mostly drawn from university campus buildings). In an earlier study, Hoelscher and Dalton (2008) utilized Weisman's set of simplified building layouts (with the inclusion of an additional two plans) in order to study the effect of presentation mode and expertise on subjective judgments. In Hoelscher and Dalton's earlier study, the modes of presentation used were plans (elementary diagrammatic corridors) and walkthrough movies whose path traversed the 'maximally possible' distance through the corridor-system, without resorting to backtracking or duplication (see figure 1 for an example stimuli from the first experiment). The movie-paths were reused for the follow-up experiment. In total 166 participants successfully completed the previous experiment (52 were architects or had an architectural education and 114 could be considered 'non-experts' or laypersons).

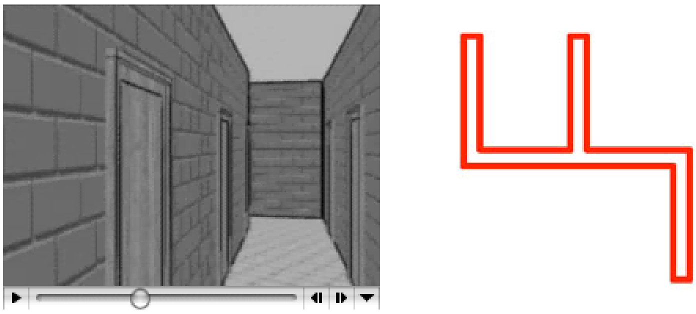

Figure 1. *Layout-stimuli as ego-centric movie (left) & abstracted plan (right) from Hoelscher and Dalton's 2008 online experiment.*

2.2 PARTICIPANTS

20 subjects participated in the CAVE™-based, follow-on experiment, of which 6 were architects or had an architectural education (constituting 30% of the subjects compared with 31% in the first experiment).

2.3 MATERIALS

In this second, follow-up experiment, a sub-set of Weisman's original thirty layouts was selected, resulting in 6 test-layouts and one additional, common, training level. The selection of the six layouts was intended to be a representative sample of the original thirty, balancing features such as symmetry/asymmetry and the number of axial lines (lines of sight), whilst simultaneously eliminating some of the simpler layouts used by Weisman and furthermore representing those materials resulting in a high differentiation both between modalities and domain expertise in the first experiment. These six layouts were modeled in 3D (see figure 2 overleaf) and a virtual reality simulation was produced of all the seven corridor systems. A virtual reality CAVE™ was used to conduct this study; this is a cube-shaped room, each side of the room being approximately 3m in size. A stereo, real-time image is projected onto three of the walls and onto the floor. During the experiment, the subjects wore lightweight shutterglasses permitting the illusion of three-dimensional depth (due to the difference in stereoscopic vision experienced in each eye). They controlled their movement through the environment using a hand-held tracking unit. Their position was also tracked and recorded in real-time. A photograph of a subject participating in the experiment is shown in figure 3.

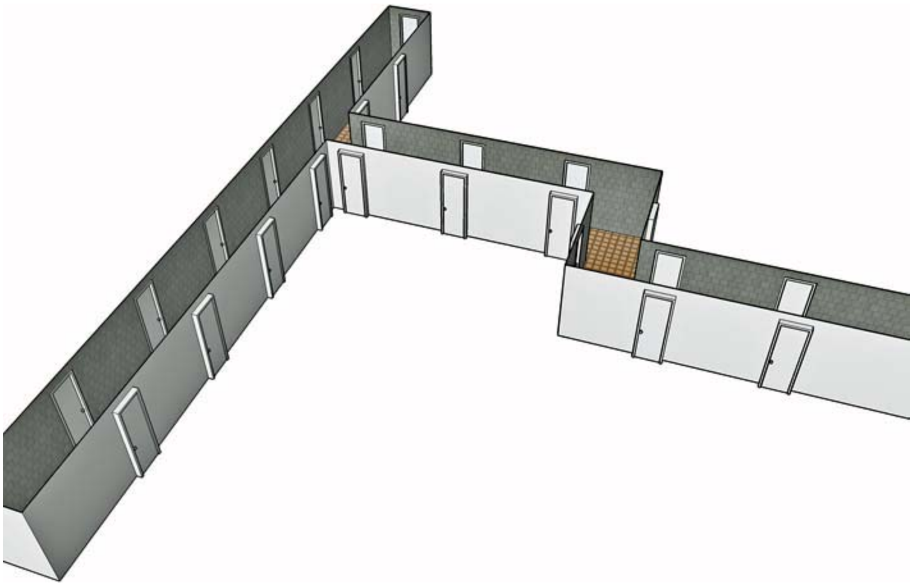

Figure 2. A typical corridor layout (layout 21) modelled in 3D.

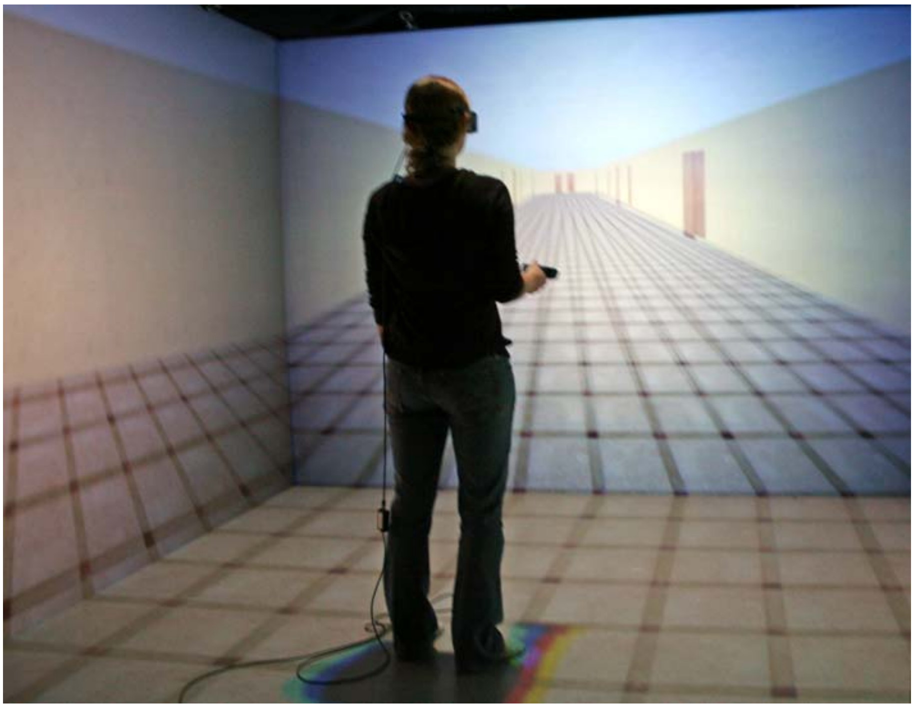

Figure 3. Subject participating in the experiment, actively navigating through a corridor-layout.

2.4 PROCEDURES

The subjects were initially introduced to the training level, and the experimental procedure was both verbally introduced and practiced. Once satisfied that the subjects understood the task, and were comfortable with the navigational controls, the first of the six test-layouts was presented to the subject. The order of the layouts was fully randomized between subjects to prevent any learning effect.

At the start of each new layout, the subjects were instructed to listen carefully for a pre-recorded set of instructions, which would guide them from their starting point (location A) to a destination (B). The routes from A to B were identical to the 'maximally traversable' path used to produce the walkthrough movies in the earlier experiment. The instructions were, for example, 'turn left' or 'continue straight on'. Once the subject reached the destination, location B, they were then instructed to attempt to return to their starting point (location A) without assistance and to inform the experimenter when they thought that they had successfully reached this location.

Once they were at location A (or where they assumed location A to be), they were then asked (via text and images appearing on the CAVE™ walls) to rate on a scale of 1 to 9 (using a Likert scale) how complex they judged the building layout through which they had just navigated (i.e. overall how intelligible they found the environment and how easily they had remained oriented throughout the experiment). A second rating task elicited their perceptions of how difficult or easy they thought that the corridor system was to navigate around (this was based on the self-perceived straightforwardness and efficiently with which they performed the wayfinding task from B to A).

At the end of the test-corridors, the subjects were asked to complete a rating test (on both complexity and navigability) on the full set of the thirty two (Weisman-plus-two) corridor plans from the previous experiment in order to facilitate an additional comparison of the results of this experiment with the earlier experiment. The total time spent by each subject within the CAVE™ environment was approximately 20-30 minutes. Subjects were instructed that they could pause and rest or terminate the experiment at any point.

2.5 MEASURES

The routes (continuous location and time) taken by each of the subjects were recorded. A subset of this data, the initial paths taken by the subjects (the first guided path from A to B) in the six layouts selected, is shown in Figure 4 below. The subject's complexity and navigability ratings for each layout were recorded manually. Numerous, objective measures of the layouts were produced in order to compare with the subject's ratings. See section 3 for a full explanation of the environmental measures calculated.

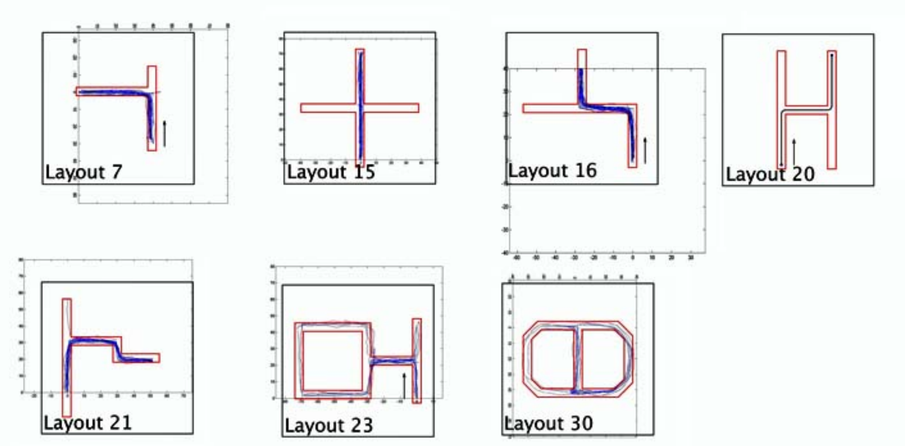

Figure 4. *Layout-stimuli as abstracted corridor systems, showing initial guided paths (from A to B) of the subjects.*

3 Environmental Measures of Complexity/Navigability

The ability to compute the complexity of a building can be of great help in evaluating design decisions, in comparing and classifying plans as well as being particularly useful as a fitness function for generative design (Jackson 2001). In Hoelscher and Dalton's 2008 study, they reviewed a number of methods of objectively evaluating the complexity of a building layout, utilizing a number of techniques of analyzing plan-based data. These can broadly be classed as four types of analysis: geometric (based on geometric characteristics of the building), visibility-based measures (based on properties of the visual field of a hypothetical situated observer located within the study-environment, configurational measures (measures that are systemic in their approach, they take in account part-and-whole relationships between discrete, constituent sub-elements of the layout and, finally, information-theoretic measures, which consider the plan as a 2D source of layout information, and attempt to measure the amount or degree of information contained within such a representation. There is a high degree of interdependency between many of the measures presented here (Hoelscher and Dalton 2008). A selection of these measures are presented below.

3.1 GEOMETRIC MEASURES

One of the earliest papers on building layout complexity was by O'Neill (1991). In this paper, he introduced a measure of 'ICD' (1981) or *interconnection density*. For each location in which a change of direction must be made (a node) the number of directional choices is noted: this is 1 for a dead-end (the only choice is to turn around and go back), 2 for a 'corridor-turn' and 3 for a T-junction etc. These values are summed for the entire layout and then divided by the total number of nodes in the building.

O'Neill found a strong and significant correlation between judged complexity and average ICD value ($r=0.78$, $p<0.01$). The ICD value was calculated for each of the layouts, as well the corridor area, corridor perimeter, the numbers of axial lines (the fewest and longest lines of sight in the building (Hillier and Hanson 1984)) and the total number of discrete convex spaces in the layout (ibid). In addition to these measures, the number of corridor segments, 'topological holes' (i.e. a cross would contain zero 'loops', a square one 'loop' and a figure-eight two 'loops') and the number of decision points (including dead-ends), were also noted. Another measure of the geometrical form of the layout which was considered was the number of lines or rotations of symmetry present. Finally the convexity of the layout was also considered, as this measure was found to be particularly predictive of subjects' ratings in the earlier study. Convexity is a measure developed by Batty (2001) and is defined as the ratio of the radius of an idealized circle associated with the actual area of the [polygon] to the radius of an idealized perimeter from the actual perimeter in question... [Ψi] varies from a value of 0 for a straight line [polygon]… to 1 for a circle… This measure falls within [the range 0 to 1 and] appears to covary with the convexity of the space."

Additionally, a number of path-based measures were also calculated, the path length, and number of path-turns etc.

3.2 VISUAL MEASURES

Another family of measures are concerned with the visual properties of a building layout and use the concept of an isovist (Benedikt 1979): a two-dimensional, planar slice cut through the potential field of view generated from a single point in space. This is usually held to be the full 360° (potential) field of view and is typically generated at average eye-height parallel to the ground-plane. The measures that were considered were the minimum number of isovist locations required to completely 'view' the whole system (for example, a straight length of corridor can be viewed in its entirely from a single location, as could an L-shaped corridor, but a U-shaped corridor would require two such locations to be inhabited to render the layout fully visible. By flood-filling a corridor system with an array of isovist-generating locations, and then calculating the area of each isovist at every point in the array, a mean isovist area for the whole layout can be calculated, as can other average isovist characteristics, such as the mean isovist perimeter, 'compactness' (an area to perimeter type measure) and occlusivity (ibid), to name but a few.

3.3 CONFIGURATIONAL MEASURES

Configurational measures are ones that take into account the relationship between discrete sub-units of space (for example, the axial line, convex space (Hillier and Hanson,1984) or isovists (Benedikt, 1979)) and their placement within the whole interconnected system. The attributes of each discrete sub-unit can be calculated, for example, their accessibility within the system (mean depth, integration, total depth) and an average value can then be calculated for the whole layout. They are predominantly used in space syntax research (Hillier and Hanson, 1984).

3.4 INFORMATION THEORETIC MEASURES

Information theoretic measures (derived from early work of Shannon and Weaver, 1948) are those that attempt to consider the amount of information conveyed in the 2D plan representation of the layout. Many of the calculations of design complexity focus on either linear elements (corridor segments, routes, paths, lines of sight etc.) or one-dimensional elements such as junctions, turns or decisions points.

In this study such measures were applied to both the corridor walls (or the 'contour' of the overall corridor layout) and to the users-path through the system (representing the more typical linear-type element of analysis). There is some precedent for attempting to use information theory to analyze building plans. Recently, such techniques have been applied to building designs by Gero and Jupp, (2002), in which building plans are assessed using an entropy-based measure applied to string-encodings of building layouts.

In this study, we used three main methods of information theoretic measures. First, a method developed by Leeuwenberg (1968) known as structural information theory (SIT) in which he attempts to encode a layout in a minimal manner, but based on perceptually-derived sub-units. The use of structural information theory in this paper is a direct application of Leeuwenberg's methods.

Second, we applied Titchener's methods (2005) of calculating the complexity of a character string using a T-code set. These were applied to a number of strings representing both the 'contour' of the layout as well as the users' paths. These strings were produced using a simple 'turtle-draw' type encoding. These methods produced a series of values.

Finally we applied Kolmogorov-Complexity-inspired measure (Li & Vitanyi, 2008). The principle idea behind this complexity measure is to describe a computational problem by the length of its minimal algorithmic solution. For the present domain, we algorithmically describe the path through the layout by the minimal number and sequence of changes-of-direction and variations in segment-lengths. While the main analytic approach is quite similar to the string-based analysis sketched, it is an open question which variant captures more of the human assessments here.

4 Results

The following analyses look at the relation of participant ratings of complexity and ease and relate them to the same ratings from the earlier study (Hölscher & Dalton, 2008) as well as to environmental variables. The training layout was included in this analysis to extend the variability of environmental features. This analysis is to be considered as preliminary. All other dependent measures will be analyzed and reported elsewhere and a more detailed analysis may include changes to the variables analysed here. The analyses in this section are based on individual data points for each participant and layout (N=146 for CAVE data, N= 242 for plan view and movie view data from Hölscher & Dalton, 2008)[1]. First we look at the overall ratings of complexity and ease of navigation aggregated for both 'experts' and 'non-experts'.

A factor analysis (orthogonal factors, VARIMAX rotated) was conducted across all environmental features to reduce the number of candidate environmental feature for the following analysis. The factor analysis revealed 7 interpretable factors. For the majority of theoretically interesting groups of factors (geometrical factors; isovists measures; information theoretic measures) we find a substantial correlation with the first factor. On this basis we maintained only a subset that a) either had been reliable in the preceding study or b) was the highest (or second highest) ranking representative of its categories and was linked to separable theoretical concept, thus eliminating several derivative measures of isovist properties or string-based complexity. Table 1 report for each of the remaining variables' highest loading factor and correlation with that factor.

The best environmental measures that predicted subjects' estimates of complexity were the number of axial lines (Pearson's r = .678, for p-values, refer to table 1), the number of convex space (r=0.646), O'Neil's ICD measure (r=0.727) and the minimum number of isovists required for full coverage (r=0.660). As well as these measures, a selection of the information theoretic measures performed extremely well, for example, Leeuwenberg's SIT method (r=0.679) and Tichener's T-codes applied to a minimally compressed contour string (t-complexity) (r=0.730). On the whole, Tichener's algorithms appear to perform best when applied to the corridor layout 'contour' rather than to the path through the layout.

[1] The same analysis was also conducted after aggregating data over participants, resulting in correlations across layouts only (N=7). That analysis yields statistically very similar results, yet numerically different values.

Table 1. Environmental features: correlations with ratings & factor analysis

		Cave Complexity	Cave Wayfinding	Factor	Correlation with factor
Axial Lines	r	.678**	.661**	1	.898
	p	.000	.000		
Convex Spaces	r	.646**	.633**	1	.790
	p	.000	.000		
Topological Holes	r	.600**	.595**	1	.732
	p	.000	.000		
Convexity	r	-.579**	-.577**	1	-.758
	p	.000	.000		
Symmetry	r	-.237**	-.201*	4	.675
	p	.004	.015		
ICD	r	.727**	.698**	1	.622
	p	.000	.000		
Leeuwenberg	r	.679**	.639**	1	.690
	p	.000	.000		
Kolmogoroff	r	.670**	.669**	1	.779
	p	.000	.000		
Contour String T-Code	r	.730**	.714**	1	.749
	p	.000	.000		
Path String T-Code	r	.688**	.663**	1	.944
	p	.000	.000		
Min. No. of Isovists	r	.660**	.636**	1	.711
	p	.000	.000		
Isovist Min. Radial	r	.417**	.440**	7	.773
	p	.000	.000		
Isovist Perimeter	r	-.425**	-.400**	2	.991
	p	.000	.000		

This pattern of extremely high correlation coefficients is replicated for the subject's estimates of the ease of wayfinding in the system, with the number of axial lines (r = .661), the number of convex space (r=0.633), O'Neil's ICD measure (r=0.698) and the minimum number of isovists required for full coverage (r=0.636). Leeuwenberg's SIT method (r=0.639) and Kolmogoroff's complexity analysis (r=0.669). See table 1 below for the results of all subjects combined ratings.

Once we begin to separate the 'experts' from the 'lay persons' there is a slight increase in the correlation coefficients, for both judgements of complexity and wayfinding ease, but since all the values are so high, these differences are extremely slight and hence inconclusive[2].

In terms of the differences between modalities, there is a clear pattern of far higher correlations with environmental measures, for those judgements elicited in the CAVE™ than for either the plan or movie modalities (see tables 2a and 2b): For the measure, the number of axial lines r increases from r=0.304 (plan mode) to r=0.678 (CAVE™ mode) for ratings of complexity and from r=0.245 (plan mode) to r=0.661 (CAVE™ mode) for wayfinding. For convex spaces the correlation coefficients increase from r=0.233 and 0.269 (complexity and wayfinding) to r=0.247 and r=0.633 by altering from plan mode to CAVE™ mode. This pattern is mostly replicated across all of the measures that performed well in the CAVE™ setting. For the majority of these correlations between environmental features and complexity or wayfinding ratings, the correlation for the rating obtained in the CAVE™ is significantly higher than either the plan- or movie-based rating (significance is based on Fisher's z, after r-to-z transformation), while no such reliable difference is obtained between plans and movies.[3]

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[2] A more sensitive approach to identify expert-layperson differences for this study might be separate analyses for individual layouts. In the previous study we had identified that for some pairs of layouts the preference pattern switches between experts and novices. Such direct comparisons are a promising tool for further analysis here, too.

[3] The present analysis looks only at the 7 layouts that were part of the present study. Here we find no significant differences between the predictive power of individual environment features for plan vs. movie mode. Across the original 32 layouts, and aggregated over participants in the original study, correlations as well as differences between correlations were much higher and such a modality effect was found. The smaller sample here under-estimates the impact of plan vs. movie modality. In this light, the large difference to the correlations for the CAVE modality is especially remarkable.

Table 2a. Correlations of features & complexity rating for different modalities, & z-value of difference between modalities (* p <.05, ** p <.01)

		plan complex	movie complex	Cave complex
Axial Lines	r	.304**	.281**	.678**
	plan (z)	0	0,50212723	5,632**
	movie (z)	0,502	0	5,908**
Convex Spaces	r	.269**	.247**	.646**
	plan (z)	0	0,47051819	5,424**
	movie (z)	0,470	0	5,683**
Topological Holes	r	.211**	.196**	.600**
	plan (z)	0	0,312	5,273**
	movie (z)	0,312	0	5,445**
convexity	r	-.340**	-.289**	-.579**
	plan (z)	0	1,130	3,378**
	movie (z)	1,130	0	4,002**
Symmetry	r	-.242**	-.237**	-.237**
	plan (z)	0	0,105	0,058
	movie (z)	0,105	0	0
ICD	r	.374**	.347**	.727**
	plan (z)	0	0,619	5,827**
	movie (z)	0,619	0	6,169**
Leeuwenberg	r	.406**	.382**	.679**
	plan (z)	0	0,567	4,365**
	movie (z)	0,567	0	4,678**
Kolmogoroff	r	.311**	.282**	.669**
	plan (z)	0	0,634	5,385**
	movie (z)	0,634	0	5,73**
Contour String T-Code	r	.389**	.358**	.730**
	plan (z)	0	0,719	5,704**
	movie (z)	0,719	0	6,101**
Path String T-Code	r	.331**	.305**	.688**
	plan (z)	0	0,577	5,507**
	movie (z)	0,577	0	5,826**
Min. No. of Isovists	r	.305**	.275**	.660**
	plan (z)	0	0,65393712	5,261**
	movie (z)	0,653	0	5,621**
Isovist Min. Radial	r	.132**	.107**	.417**
	plan (z)	0	0,506	3,427**
	movie (z)	0,506	0	3,706**
Isovist Perimeter	r	-.252**	-.255**	-.425**
	plan (z)	0	0,064	2,160*
	movie (z)	0,06400026	0	2,125*

Table 2b. Correlations of features & complexity rating for different modalities, & z-value of difference between modalities (* p <.05, ** p <.01)

		plan wayfinding	movie wayfinding	Cave wayfinding
Axial Lines	r	.245**	.258**	.661**
	plan (z)	0	0,277	5,995**
	movie (z)	0,277	0	5,842**
Convex Spaces	r	.233**	.245**	.633**
	plan (z)	0	0,254	5,60**
	movie (z)	0,254	0	5,465**
Topological Holes	r	.187**	.201**	.595**
	plan (z)	0	0,290	5,463**
	movie (z)	0,290	0	5,302**
convexity	r	-.309**	-.281**	-.577**
	plan (z)	0	0,612	3,727**
	movie (z)	0,612	0	4,065**
Symmetry	r	-.099**	-.111**	-.201*
	plan (z)	0	0,242	1,150
	movie (z)	0,242	0	1,016
ICD	r	.276**	.288**	.698**
	plan (z)	0	0,260	6,386**
	movie (z)	0,260	0	6,243**
Leeuwenberg	r	.272**	.283**	.639**
	plan (z)	0	0,237	5,257**
	movie (z)	0,237	0	5,126**
Kolmogoroff	r	.266**	.263**	.669**
	plan (z)	0	0,0643	5,906**
	movie (z)	0,064	0	5,941**
Contour String T-Code	r	.295**	.294**	.714**
	plan (z)	0	0,021	6,510**
	movie (z)	0,0218	0	6,522**
Path String T-Code	r	.251**	.264**	.663**
	plan (z)	0	0,277	5,964**
	movie (z)	0,277	0	5,811**
Min. No. of Isovists	r	.245**	.257**	.636**
	plan (z)	0	0,255	5,520**
	movie (z)	0,255	0	5,379**
Isovist Min. Radial	r	.180**	.157**	.440**
	plan (z)	0	0,472	3,195**
	movie (z)	0,472	0	3,456**
Isovist Perimeter	r	-.120**	-.141**	-.400**
	plan (z)	0	0,426	3,337**
	movie (z)	0,426	0	3,101**

4. Discussion

The previous study by Hoelscher and Dalton (2008) suggested that non-architect's ratings of complexity versus wayfinding differed between presentation mode (demonstrating far greater differences between plans and movies compared to the ratings of the 'experts' who were far more stable across the two modes). In this study, both groups increase their ratings in the CAVE™ mode, to such an extent that there is no longer a great difference between the performances of the two groups. These similarities combined with uniformly high correlation coefficients make it particularly difficult to state whether the differences found in the level of expertise still play a role, once the environment has been simulated in the virtual reality CAVE™.

In the first study it was also shown that architects perceived the same materials to be simpler in plan mode, in contrast to the laypeople who rated the layouts as simpler when presented as movies. The initial and tentative interpretation of this finding was that experts are far more familiar with assessing plan views, while laypeople have greater difficulties interpreting plans and thus find movies easier to comprehend. This early finding is upheld by the subsequent performance of both groups in the CAVE™ environment. It is as if, from the perspective of the layperson, their ratings increase the closer to 'reality' they come, with the CAVE™ environment being closer to a real environment, compared to the plans and movies used in the previous experiment. For architects, in contrast, despite the fact that their rating correlations improve in the CAVE™ environment, they correlates well with objective measures of layouts in both plan and movie modes, suggesting that their expertise in reading plans, permits them to imagine 'reality' without needing a mode of representation that is closer to it.

These findings suggest that the CAVE™ environment is an excellent mode in which to test subjects' judgments of layout complexity and ease of wayfinding. It could be argued, of course, that the uniformly and unusually highly correlative ratings of both groups might suggest that the CAVE™ is less suitable for such research. We would like to suggest that these surprising results might be attributed to two factors: first, the relatively low numbers of participants (n=20) and the relative simplicity of the seven layouts. We are currently working on a full analysis that will also include behavioral data from the CAVE™ environment with additional measures. Beyond this, we suggest that there are two prominent ways to develop this work in the future. This study should be extended but with far more complex building layouts utilized as test-environments, in order to elicit a greater range of responses. Also, that a study, similar to Weisman's original study (1981), where judgments of both wayfinding and complexity are made in the real world, and that this additional stage be incorporated into the study. In this way, the effect of mode of presentation would range from 2D plan to walkthrough movie, to virtual reality CAVE™ and finally to a realized building. This can then be matched to both measures of building layout complexity and of level of expertise of the subject.

5. Acknowledgements

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Pedestrian Route Choice Simulation Using Mixed Methods

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Abstract. This paper presents three methods of representing space and finding shortest or least cost paths for the purpose of pedestrian movement simulation in complex built environments. It evaluates the advantages and disadvantages of these methods and the benefits of mixing them in order to throw more light on plausible route choice models that take into account cognitive factors in pedestrian way-finding and route choice.

Keywords: representation, space, route choice, wayfinding, shortest path, angular, distance.

1 Introduction

Determination of optimal paths in complex buildings is an open research question. Estimating more realistic route choices for the purpose of simulation would be desirable from a number of perspectives. These perspectives include the optimization of building design for ease of wayfinding; accurate prediction of crowding in emergency evacuation scenarios and accurate prediction of movement patterns in scenarios of normal use. In addition, such findings could also be used in assisted navigation technologies and to facilities management applications. However, when it comes to creating a description that is tractable to different analytic and simulation techniques, the current state of the art is fraught with unsatisfactory trade-offs between different representational paradigms. A discussion on the pros and cons of each are presented in [1]. In urban morphological research, correlations between these topological analysis and movement often provide better correlation coefficients than those of traditional origin-destination type simulation models [2,3]. However, Sailer [4] notes that not all office buildings demonstrate a good correlation between movement and traditional Space Syntax measures such as integration (as defined in [5]). Sailer provides a tentative explanation that certain types of office operate differently due to their organizational culture and potentially different social ordering. We hypothesize that schools (although not analyzed by Sailer) fall into this latter category of complex building. Given the uncertainty of knowing how well Space Syntax methods predict movement in a subset of complex buildings, how can we be sure that, whichever method we apply, we are actually accurately and successfully predicting correct pedestrian route choices in environments whose function and use are relatively controlled? The need to provide useful information on such buildings has led to the exploration of a mixed-mode approach to building representation for the purpose of pedestrian route choice analysis and simulation. This paper presents a real world school environment, with a complex spatial structure, coupled with a route-choice scenario that allows us to compare three different alternatives for the representation and selection of a route from one classroom to another. The three alternatives are: visibility graph (VGA) and isovist analysis [7], voronoi-based route graphs [6] and the Yamamoto semantic map modeling tool [8,9].

2 Method

For the purpose of the research, a representation of the school environment was created for the ground floor of the building. The case-study building is a new academy school in the midlands in central England that opened in September. The route choice scenario was a path between two classrooms across the main atrium from one another: classroom AS02 to classroom S05 and vice versa (see fig. 1). This particular route choice situation was selected on purpose for its likelihood of producing divergent routes under different algorithmic treatments. Not all such scenarios would have been equally likely to produce divergent results. Future work on this project will take a large sample of varying scenarios to control for environmental variations that would affect both algorithms.

Space Syntax

The first step of the methodology was to reduce the floor plan to a walkable space polygon with holes representing any permanent, full-height obstacles. This would form the underlying base trace for both Space Syntax analysis [6] and voronoi-based route graph creation [1]. The ground floor was then analyzed in Depthmap [7] for integration (fig. 2) and for picking out isovists at key points in the spatial layout (fig.7). The integration pattern of the visibility graph of this floor highlights the southern corridor as the more integrated and hence more likely to be used and/or traversed circulation space under generalized usage conditions.

Yamamoto

The floor plan was also represented as a collection of polygons for each semantically meaningful room or circulation space. This representation was necessary for input into the Yamamoto software. Figure one shows the result of the Yamamoto modelling software and a route from the entrance to the school to the foot of the dining room stairs using the inbuilt pathfinder algorithm in the software. The pathfinder module uses an A* search algorithm on the network of boundaries for the entire 2D floor area in order to produce a path that minimizes distance and angle simultaneously [9,10]. This path follows the same corridor highlighted in the visibility graph analysis (fig. 2) as more integrating. Such a comparison indicates the likelihood of a potentially high correlation between minimum distance routes and visually integrated routes in spatial complexes. The same procedure was carried out to determine the route for the case-study scenario set out above (fig. 5).

Voronoi

The voronoi-based route graph, produced by J.O.Wallgrün, is presented in figure 3. It is a 1.5D network on which origin-destination type models can be run. One advantage of this type of representation over the Yamamoto or VGA representations, are the ease of identifying the decision points within the space structure of the building. These decision points are simply any vertex in the route graph with a degree of 3 or higher and represent parts of the building where users need to make a decision between two or more paths along their journey. A subset of these types of vertices is the c-space in space syntax terminology [5].

Hybrid Technique

The next step was to derive the dual graph from this network following the procedure originally suggested by Batty [11] as a way to bridge the gap between origin-destination representations and space syntax representations. The novelty however lies in applying the technique set out in [11] in the inverse. The full description of how to implement this routine is set out in [1]. Figure 4 presents the dual graph as created for the current floor plan layout. Once these two complementary representations were created, Djikstra's least cost algorithm [10] was applied to each one, resulting in a shortest distance route and a least angle route (fig. 6).

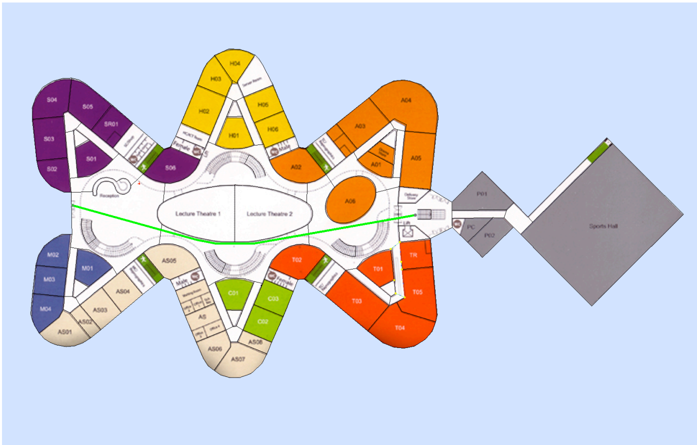


Figure 1: The School Building Modelled in Yamamoto semantic map modelling software showing a sample shortest route from the entrance on the left of the building to the foot of the dining room stairs on the opposite side of the building.

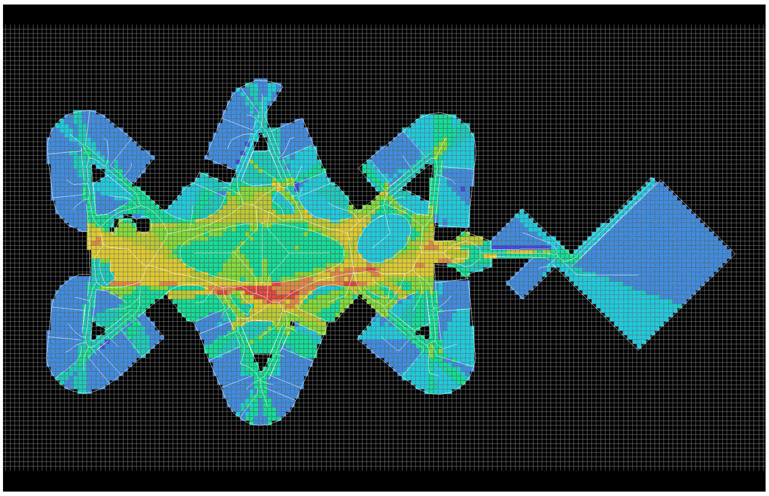


Figure 2: The ground floor of the school building analyzed in Depthmap (VGA software). The colours indicate the integration (Hillier & Hanson 1986) values of the floor plan using overlapping isovists. The lower corridor is highlighted as more visually integrating than the upper corridor. In this example the visibility analysis and Yamamoto shortest path selection method would both highlight the same route from entrance to the foot of the dining room stairs.

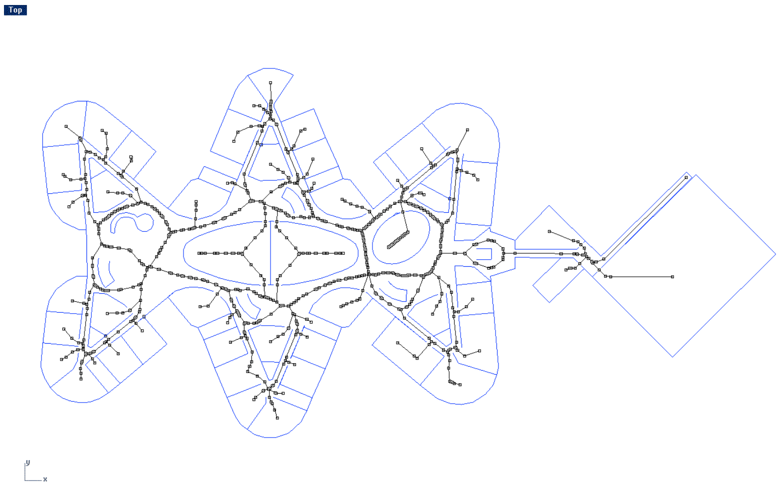


Figure 3: A Voronoi-based route-map representation of the school using the method proposed by Wallgruen 2005. This representation provides a skeleton network that represents the topological layout of the school in a planar manner that is equivalent to the representation of cities using road centre-lines as the basis for network simulation and analysis. This allows for a shortest path calculation based on metric distance travelled over the links/edges in the network.

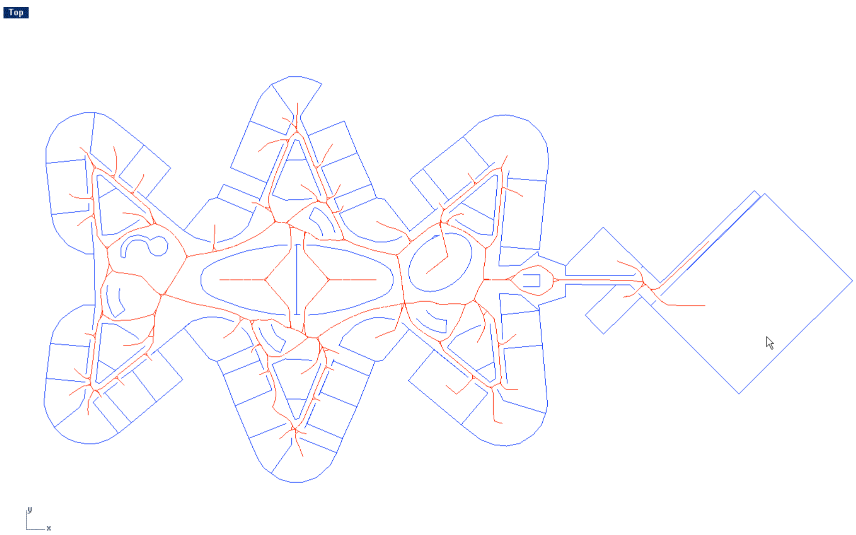


Figure 4: The dual network of the route map in fig.3. This representation allows for the calculation of the shortest path between two vertices in terms of minimum angle turned through the links/edges in the network.

3 Results

The result of selecting a route between classroom AS02 and S05 in Yamamoto, illustrated in figure 5, shows the minimum distance and angle path in one. The path selected is almost a straight line from one classroom to the other, except for a couple of sharp changes in direction at each end of the route. It happens to follow the outline of the building and remain in geographically remote areas of the floor plan with respect to the results of the VGA analysis.

The results of selecting a route using Djikstra's shortest distance algorithm in the voronoi-based graph highlights a similar path to the one picked out using Yamamoto (fig. 6a). The only difference is that the line of movement has not been optimized to iron out the kinks in the changes of direction. This is due to the dimensionality reduction inherent in such an encoding, which is described as a 1.5D representation [13]. The consequence of selecting a route using Djikstra's least cost algorithm on the dual of the voronoi-based graph, on the other hand, that represents the angular distance between edges in the original representation [11], are such that a new path is selected as the least cost way of getting from A to B (fig. 6). This route goes closer to the topographical and topological centre of the school and avoids the large changes in direction at either end of the former, minimum distance sequence. As mentioned in the methodology, each vertex of degree 3 or higher in the voronoi-based graph represents a decision point for the pedestrian in navigating the school. It is clear then that the view from these decision points might influence wayfinding and route choice behaviour, especially for those unfamiliar with the built environment. The isovists from the first and last decision points along the way from AS02 to S05 (fig. 7) therefore delineate the visible space at key moments on the path from one classroom to another. In this scenario it also happens to be the case that the path that reveals itself visually the most from the key decision points is the least angle one. It would, however, be possible to have a scenario where there might be a third, divergent, path which was more visible from the start of a route and yet which minimized neither distance nor angular change of direction. Such cases need to be found and tested exhaustively theoretically as well as empirically in future studies.

4 Conclusions

The results of this preliminary study into route choice selection via the different algorithms and representations presented above highlights the sensitivity of such automated procedures to select for different paths. The question is: which algorithm is most appropriate or plausible in simulating the route choices of real people? This critical question cannot be answered based on the work presented in this paper alone. For now, however, the results highlight the possibility that using an angular distance algorithm for the estimation of route choice seems to guide space-users through more integrated spaces than a distance-based algorithm. In order to prove this conclusively a larger sample of origin-destination pairs need to be analysed against the Space Syntax data. This will also settle how often these two algorithms deviate from one another in a real-world scenario. Space syntax has placed the perception of people back into the heart of the prediction of movement, busting the ‘homo economicus’ myth. However, its results are often generalized into a framework of perceptual physics, reducing the ability to simulate the individual intentions of one person. By further testing and exploring such a mixed method approach to route choice selection algorithms, more realistic models of people movement in the context of free will and individual intention will be made possible.

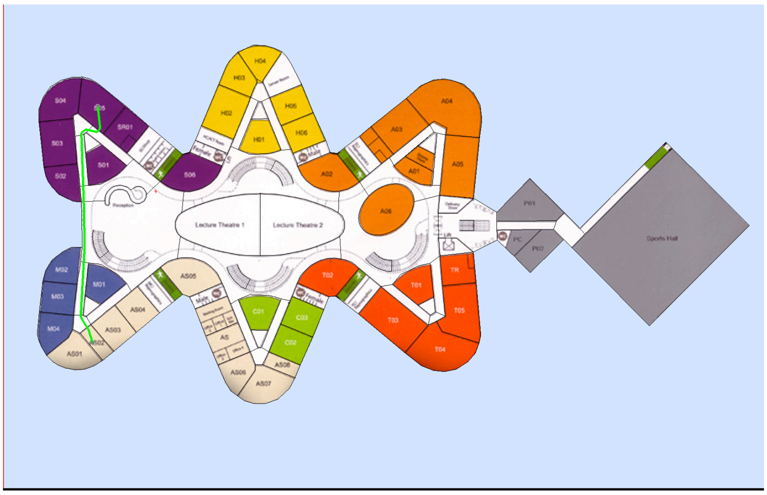


Figure 5: Case study Origin-Destination Pair from AS02 to S05. The shortest route computed by Yamamoto follows the corridors along the building perimeter. It thus indicates that pupils would choose this path to go from A to B and back.

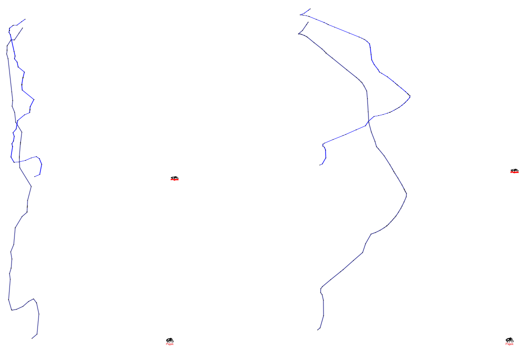
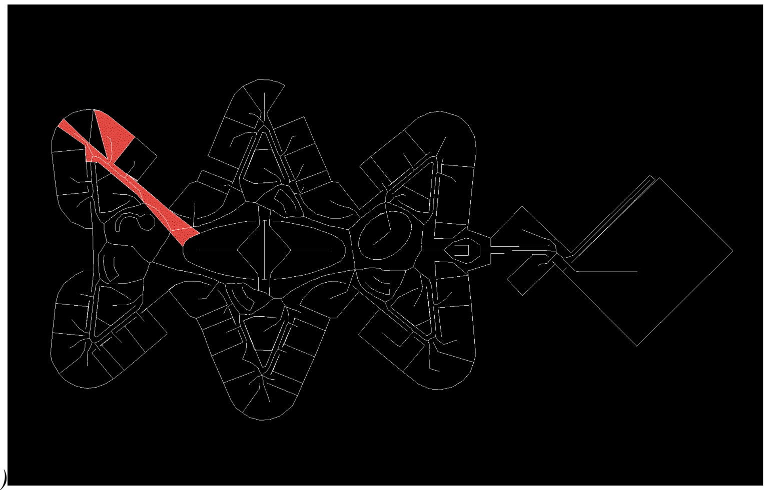
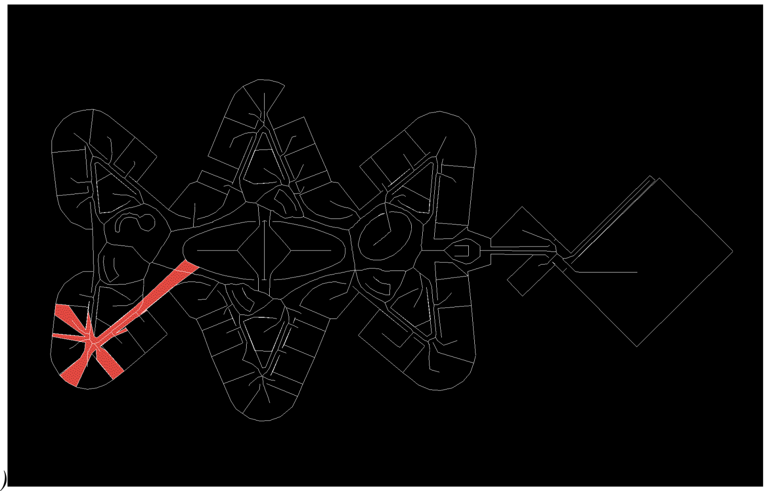


Figure 6: a) The shortest route calculated using the length of the in the route map representation (fig. 3) highlights a similar route to the one picked out by Yamamoto (without the angle minimising algorithm). b) The shortest route calculated on the dual graph of the route network using the angular distance between edges picks out another route from Yamamoto and the standard path in 6a. This path traverses the atrium closer to the centre of the building rather than following the building perimeter.



a)



b)

Figure 7: The isovists taken from the first a) and last b) decision points that are common to both routes in fig. 6. Visual inspection shows that the minimum angle path is more visible from these decision points than the shortest distance path. If path choice is affected by the amount of space visible as predicated by Turner's EVAs, then the minimum angle path is a more cognitively plausible route choice than the minimum distance path, even if both algorithms assume total knowledge of the space system under study.

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The Visual Properties of Spatial Configuration

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Abstract. This paper is a first step in understanding whether the spatial geometry of the environment has visual qualities that are used during navigation. It reports the results of a study which seeks to identify visual variables that represent spatial configuration. A novel method for approximating the pedestrian visual experience uses a series of 360 degree photographs taken along three routes in the City of London. Six image properties are identified that are held to be representative of spatial configuration: visual connectivity; percentages of visible sky and floor areas; ratio of sky to floor area; the maximum road centre line and the maximum depth of view. Each variable is correlated with several space syntax measures. The results show that these variables do represent properties of spatial configuration, and that they should be used in a subsequent behavioral study.

1 Introduction

Can the analysis of the geometrical properties of the environment, together with its visual attributes, improve the space syntax model to make it relevant at the level of the individual? Isovist analysis has been used to suggest that geometrical aspects of the environment may be linked with behavior (see discussion below). This paper seeks to contribute to the field by investigating the visual attributes of the geometry of the environment. It reports the results of a study in which the pedestrian visual experience was approximated by a series of 360 degree photographs taken along three routes in the centre of London. Six variables were measured off each photograph; the variables were chosen to represent the topological and geometric nature of the local to global information that constitutes the configuration of urban space. These six visual properties were then correlated with space syntax measures.

This study was conceived of as a first step towards the overall research goal. It was therefore judged to be more useful to identify factors that reflected properties of spatial configuration than to begin with a behavioral study. It is hoped that the visual variables identified in this study will prove relevant in a subsequent behavioral study.

The paper begins with an overview of existing relevant studies. The main part of the paper reports the methodology and analysis of the study. The results show that there is evidence that these six variables represent spatial configuration. The paper ends with a discussion of the limitations of the present study and of suggestions for future research.

1.1 Space Syntax and the Individual

Space syntax provides an environmental model that is equipped to analyze the relation of local to global scales. In terms of theory, space syntax is concerned with how the continuous system of space (in an urban setting, everything that surrounds buildings) can be broken down into discrete spaces. One of the most common methods involves drawing the longest and fewest lines of sight with potential for movement in the urban environment (known as axial lines). This spatial configuration is then abstracted to its topological connections (an axial map), which is then analyzed as a graph (for a more detailed description see [1]). The basis of space syntax theory is that the social use of space can be understood by analyzing the spatial configuration [2]. One achievement of the model is its ability to form accurate predictions on aggregate pedestrian density [3]. At the moment however the model does not allow for individual differences and cannot therefore aid our understanding of wayfinding behavior.

The issue of developing the space syntax model so as to make it relevant also at the level of the individual has gained importance in the space syntax community (see [4] and [5]). Two important experiments have, using space syntax, directly related spatial configuration with the navigational performance of subjects in open and directed search tasks in a hospital setting [6], [7]. The need for a closer examination of individual differences in space syntax analysis was revealed by the analysis of pause behavior at junctions in different virtual worlds [8]. Further research refining the space syntax model has included the relevance of the individual [9]. Moreover the use of space syntax as a post-hoc analytic tool has shown that an analysis of spatial configuration can explain aspects of wayfinding behavior [10].

1.2 Geometric properties of the environment

A promising approach across many of the aforementioned studies, looking at how effective the space syntax model can be in relation to the behavior of the individual, is the use of isovist analysis. An isovist is a 2D polygon that represents the vista around one point, its generating location. This way of representing a visual field has proved popular amongst architects and planners, in the same way as the related concept of a viewshed is used by geographers. The use of isovists to represent the visual field owes much to Benedikt [11], who claimed inspiration from Gibson's ambient optic array [12], although the concept of isovist was originally conceived of by Hardy [13] and the term coined by Tandy [14]. Isovist analysis was developed to include the interrelation between individual isovists; visibility graph analysis (VGA) is based on a multitude of generating locations and allows for a combination of local and global measurands, thus creating a model of the environment as a whole [15]. The measurands that are the cornerstone of isovist and VGA analysis record the 2D geometry of the environment (see for example [11], [15] and [16]).

Isovist and VGA analysis have proved particularly popular because abstract properties relating to the 2D geometry of the environment seem to correlate with the psychological response to that environment. The extent of this relationship still needs to be clarified, however a number of studies have shown directly that correlations exist between navigation behavior and isovist-related measurands (eg. [10], [17] and [18]).

1.3 Visual variables

This paper has taken inspiration from advances in the above studies, connecting measures from the 2D geometry of the environment to behavioral outcomes, and other studies that seek to identify cognitively-relevant measures from environmental models such as space syntax (eg. [19]). It seeks to add to the research by including a further variable, the visual properties of the environment. Advances in our understanding of visual attention, including how salient landmarks are used for navigation [20], have highlighted what factors affect our gaze bias in the environment (for a review see [21]). Such considerations will be vital in a subsequent stage of this paper which will incorporate a behavioral study, testing how the individual acts upon information in the visual properties of the environment.

2 Method

2.1 360 Degree Photography

Given that the overall research aim was to use the results from the present study to test behavioral outcomes, it was decided to recreate the pedestrian visual experience of walking along a route through a series of 360 degree photographs. This is a novel method and has a number of benefits: 1) it represents a permanent quality of the real world; 2) it accounts for the moving observer due to the sequence of images taken along a route; 3) it does not restrict the representation to the field of view of a possible viewer by providing the full 360 degree scope; this is a 2D approximation of Gibson's 'ambient optic array' [22].

A 360 degree photograph shows the full panorama around one point, that is the view of a person turning on the spot (see figures 1 – 3). Each 360 degree image was the result of the stitching together of several individual shots. A shot was taken every 36 degrees on the horizontal scale, which means that there were no less than 30 individual shots for each location: ten at the desired height, ten at +45 degrees (orientated upwards) and ten at -45 degrees (orientated downwards). These were then stitched together using specific software[1] to create a static image file, where every point along the base of the image is in effect the same point. The result was a cylindrical image which could be represented on a flat surface. The photographs were taken using a tripod, a Manfrotto 302 Panoramic Head and a digital SRL camera. The

[1] PTGui image software was used.

panoramic head allows for entirely accurate angular measurements on the horizontal (measuring every 36 degrees) and vertical (0, +45 and -45 degrees) scales; it also removes parallax error whereby distances in photographs are distorted, given that without a panoramic head there is a discrepancy between the point at which the camera rotates around the tripod and the point in the lens where the photograph is taken. The height of the lens, which was checked and leveled every time the tripod was moved, was 160cm, the average eye height for people in the UK. The photographs were taken at dawn and on the weekend in an attempt to avoid the presence of people and vehicles and to best reflect the nature of the spatial configuration. This was successful to a large extent although in certain cases the presence of parked vehicles could not be avoided. Overall about 5000 individual shots were taken.

A limitation of using 360 degree photographs is the distortion involved. First, there are problems associated with a planar image that is a representation of a spherical image. However all the images were taken and stitched together in the same way, which means that the distortion is equal for all of them; furthermore it is difficult to remove distortion in photography of this kind. Second, the image was cylindrical and not fully spherical, which means that the environment immediately above the camera and below the tripod is not represented. This is a limitation given that three of the variables derived from the photographs relied on this information. However, given that all the images were taken and stitched together in the same way, the amount of information lost is equal for all of them. Third, there is the discrepancy between units on the photograph and real world units: when measuring off the photograph, a bus and a dustbin might result in having the same height. This distortion relates to the analysis of photographs and will be discussed below.

Fig. 1. Location C1

Fig. 2. Location C2

Fig. 3. Location C3

2.2 Routes

The experiment was conducted on three routes (see figures 4 – 6 below) in the City of London, which is the historical core, and an important financial and legal centre, of London. The selection of the three routes (C, L and StP) followed a set of criteria that will be briefly described here: 1) the routes were made up of streets that had a variety of space syntax values. This was judged to be important given the type of analysis proposed; 2) routes were selected that were predominantly road-based, thus avoiding largely pedestrianised areas; 3) areas with building works were avoided; 4) streets with significant topographical differences (such as the slope down towards the river Thames) were avoided; and 5) it was deemed appropriate to attribute a semblance of reality to the routes and thus they all start near an exit of an underground/ train station and proceed towards a landmark location or another underground station.

Routes C and L both start at Bank underground station and route StP starts facing the entrance of Blackfriars station on Queen Victoria street. Route C is labeled after its destination location, on Cannon street, with the entrance to Monument underground station in view. Route L is labeled after Leadenhall market, the entrance to which can be seen from the final location on Gracechurch street. Route StP is labeled after Saint Paul's cathedral, which is visible from the final location on Ludgate Hill. An attempt was made to make the routes as comparable with each other as possible. They are therefore of broadly similar lengths (300.3m, 312.3m and 329.8m) and have similar number of turns (8, 6 and 5). (By contrast, the number of e-spaces (38, 43 and 26) could not be controlled).

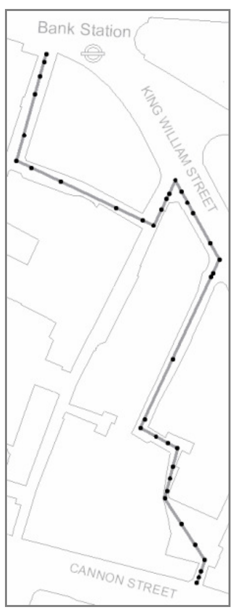

Fig. 4. Route C

Fig. 5. Route StP

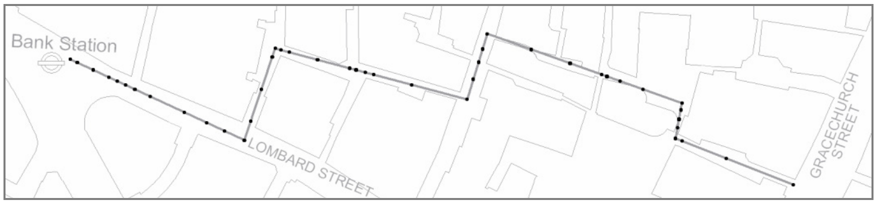

Fig. 6. Route L

2.3 Photographic Locations

It was necessary to have a rigorous method to determine the location of the photograph. The pilot study revealed that a fixed distance between locations would not be adequate, not least because there is a greater information gain around a corner which would require a greater number of locations compared to a straight segment of the route. A useful method was to decompose each route into its e-spaces [23]. An e-space is an informationally stable unit which is bounded by e-lines; by crossing an e-line, there is a significant change in information, a fact that is vital when navigating in the environment [12]. A map containing only the outline of buildings was created based on data supplied by Edina[2], upon which the e-lines were drawn. E-lines are formed by extending the diagonal that connects two corners, that is, if the line connecting two building corners can be extended it is drawn. If the extension happens to centre on another corner then the diagonal itself would also be considered an extension. For curved buildings a tangent could receive the extension but not generate it. Once the e-lines had been drawn, any ensuing e-space that was less than one meter apart from the next was discarded. The generating location for each photograph was thus bounded within an e-space; the exact location of each photograph tended to be in the middle of an e-space, unless factors such as busy roads were significant. If the e-space involved a change in direction, the photograph was taken at the corner.

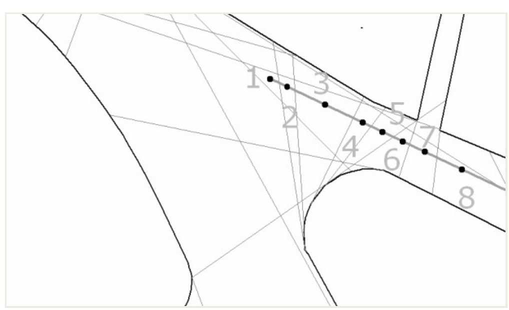

Fig. 7. E-spaces and photographic locations 1 – 8 for route L

[2] ©Crown Copyright/database right 2008. An Ordnance Survey/EDINA supplied service.

2.4 Six Image Properties

Six variables that relate to the visual properties of spatial configuration were identified, which were measured off each 360 degree image (an example is shown in figure 8 below). The variables were chosen according to a number of criteria: 1) to keep in line with the results from research investigating the psychophysical properties of isovist analysis; 2) to have variables that might be critical in a subsequent behavioral study; 3) to use variables that could usefully be understood from photographs; and 4) following the indications derived from the pilot study. A number of other interesting measures were not considered in the present study, even though they may be included in a subsequent study; this includes road width and building height, the angle of incidence of the connecting street, the junction type, and the position of the photograph along a segment. Each of the six chosen variables is described in detail below.

1. Visual connectivity (v-connectivity). Visual connectivity is the number of connecting streets visible in the photograph, not including the one on which the photograph was taken. Any indication of a connecting street was accepted, including road signs and the angle of two facades such that there must be a gap in between them. This is similar to the way in which the human eye processes indications (eg. a car about to turn onto a main road, even if it is in the distance, implies that it is coming from a connecting road).

   Connectivity is a crucial measure in the space syntax environmental model, which is based on the longest and fewest lines of sight with potential for movement (known as axial lines). V-connectivity is a new measure that is especially relevant when dealing with a visual image. It provides information about locations that are out of view and has therefore properties of a second-order visibility relationship [15], there being a hypothetical intermediary location from which the entire subsequent street is visible. The variable is also connected to the notion of a “promise of more information” which Kaplan describes through the term mystery [24]. It is a useful variable because it draws on connectivity; notice however that it is not identical with the connectivity value commonly utilized in space syntax research, which instead records only the physical and direct connections of every street. The measure used in this study, on the other hand, is for all the visible and sometimes indirect connections. It is suggested that this variable should correlate best with integration, for which calculation connectivity is important.

2. % sky area. The outline of the visible sky was drawn and the total area recorded. This was then expressed as a percentage of the total area of the photograph. All permanent and semi-permanent features in the skyline were excluded from the variable; this included church steeples, shop signs (because they are an accurate reflection of what one sees) and “to let” signs (because they are so similar to shop signs, especially when seen at a distance). Items such as flag poles and cranes were included within the sky area.

The % sky area was chosen because 1) it relates to the two-dimensional geometry of the environment, as represented in the photograph, even though intrinsically it is related to the third dimension; 2) the amount of visible sky has been proposed as a factor that influences wayfinding (see [25] and [26]); 3) it is a constant within the spatial configuration of the environment; 4) the variable incorporates information regarding building height and road width; if all the buildings were of the same height and were separated by the same road width, the values would be constant; and 5) it is a value that can easily be measured from the photographs and which, expressed as a percentage, does not involve problems of distortion.

3. % floor area. In a similar vein to the above variable, the outline of the floor area was drawn and the total area recorded and expressed as a percentage of the total area of the photograph. All small objects and items that could easily be circumnavigated were considered part of the floor area, such as lamp posts, other posts, bollards and small building works on the pavement. Areas that were cordoned off or benches placed against the wall were excluded from the floor area. In a few cases, in order to be consistent with the floor area across a sequence of photographs, it was necessary to intuit a small corner of the outline when for example it was obtruded by a vehicle.

   This variable was incorporated in the study because 1) it expresses a fundamental part of the spatial configuration upon which the space syntax model is based; 2) the floor area is important during navigation because it is what we use physically when we navigate; 3) the connection between floor area and navigation has been made in studies using isovist analysis that have correlated behavioral responses with isovist area (eg. [17]); 4) it is sensitive to road width (but not building height); and 5) there are no problems of distortion given that the measure is expressed as a percentage and is used consistently across the sample.

   A limitation of the above two variables is that they are heavily dependent on the precise location of the photograph, with only slight variations in the location affecting the measure. It was felt however that the method of producing the 360 photographs (see section 2.1) was precise and rigorous to such an extent that the variation between each photograph was rendered insignificant.

4. Sky-floor ratio. The percentage of sky area was divided by the percentage of floor area to represent the ratio of sky to floor for each photograph. It is a useful variable because it is related to the total composition of the photograph. It is the only variable which takes into account the relation between elements in the photographs, a factor favored by the Gestalt psychologists [27]. The variable could correspond to a property of spatial configuration and thus be highly significant during wayfinding. As a ratio, it does not include issues pertaining to distortion.

5. Maximum road centre line. This is the real world distance of the furthest stretch of road from the location of the photograph. That is, walking from the location of the photograph in any direction, without changing road, this is the greatest possible distance of road, measured at street level to the middle of the furthest connecting

street. It is one of the variables where the distortion within the photograph could lead to ambiguity. It was decided therefore to express the maximum road centre line not as units off the photograph but in real world meters, which also allowed for the measurement to be used directly with metric distances expressed in the space syntax analysis. As a result the longest line as seen on the photograph was recorded off the route map; if the longest line was unclear from the photograph, measurements from the route map would clarify which was longest. In each case the longest road centre line is present on every image.

This variable was included in the study because it records properties of permeability, a crucial factor in an environmental model such as space syntax and for navigation. Road centre line data has been used in conjunction with the space syntax model in other studies [28].

6. Maximum line sight. This is the furthest field of view at street level expressed in real world meters (following the same reasoning as for the previous variable).

   This variable was chosen because 1) it represents a property of accessibility, important for an environmental model; 2) it has been suggested that depth of view is a principal component of wayfinding behavior, with the related wayfinding strategy of following a linear route wherever possible, gaining increasing weight in the literature (see [29], [30], [31] and [18]); 3) depth of view represents the 2D geometry of the environment and is thus connected with measures that can be derived from isovists or a depth profile (eg. [32]). It is suggested that this variable will relate to the permeability and connectivity measures described above.

Fig. 8. Location C1 (with analysis)

2.5 Space Syntax Measurements

The space syntax model chosen for this study takes the set of longest and fewest lines of sight with potential for movement (axial lines) in the system (in this case the centre of London), and breaks them up at each junction into segments. A segment is a part of an axial line that connects two adjacent junctions; each segment begins and ends at an intersection with another line. This network is then analyzed as a graph, with the segments as nodes and the intersections as the links connecting them. The benefit of using a network based on segments rather than axial lines is that the connections between the nodes can take into account angular displacement as well as topological distance; this has been shown to better reflect observed pedestrian movement [9].

The graph is measured according to different mathematical properties that are believed to reflect urban movement (for a greater discussion of this refer to [9]). A measure of closeness, or integration, will reflect how likely it is that a segment is an origin or destination segment; a measure of betweenness, or choice, will reflect how likely it is that a segment features as an intervening space in between an origin and destination. These measures can be recorded at different scales, reflecting the variable length of journeys in the urban network; at a basic level it is helpful to distinguish between local and global scales. The scale is recorded in terms of a radius, centered on the segment in question, measured in metric distance.

The space syntax model used in this study was based on an axial map of Greater London, restricted to the area of interest (the centre of London) plus a catchment area of three miles to avoid any edge effects. All the analysis was segment angular analysis. The measure of closeness, or integration as it is commonly known in space syntax studies, was measured at a global scale (radius=n), and at two local scales, radius 100m and radius 500m. The measure of betweenness, or choice, was measured at the global scale and at the local scale of radius 300m. The selection of which radii to use to describe movement at a local scale was based on the evidence from the model itself and from preliminary results in the pilot study (see images from space syntax model in the appendix). The inconsistency of radii at a local scale between the two measures was accepted given that it was more important to fully represent the space syntax values rather than simply use the same radius for both measures.

The five chosen space syntax values for each segment of the routes were recorded. The photograph from a corner location was orientated towards the new route segment to best represent the experience of walking down the route. To be consistent with this notion it was decided that the corner location should belong to the ensuing route segment; the space syntax values of corner locations are therefore those of the subsequent route segment. This results in certain corner locations (often those on the corner of a main road with a smaller road) having variables measured off the photographs that reflect the space syntax values of the preceding route segment. A particular kind of corner location is the final location; it was decided that the final location of each route should represent an end-point rather than a starting-point for another route. Therefore the final location, always on main road, has the space syntax values of the final route segment.

The aim of this study is to see whether there are visual attributes that correlate with the predicted space syntax measure. The six visual variables that were chosen to reflect geometric aspects of the spatial configuration, are therefore correlated with the five space syntax measures describe above.

3 Results

This section presents the results from the Pearson correlation between the six visual variables and five space syntax measures described above. The analysis was performed for each route individually and for all locations when considering the three routes together. Given the scope of this study, it was decided to perform only a correlation analysis, with a predictive regression analysis to accompany a future study that incorporates behavioral data. Preliminary results suggested that the correlations with the choice measures required a logarithmic base, thus the local and global choice measures in the correlation analysis are the natural logarithm of choice. All results are significant to $p<0.01$ unless otherwise indicated.

3.1 Route C

The correlation matrix for route C shows several strong correlations, especially for all variables at global integration and integration radius 500m (see table 1). By contrast both local space syntax measures revealed less strong correlations, with the exception of local integration against both sky-related variables. Of the six recorded visual variables, the road centre line variable did not correlate as strongly as the others. The strongest correlation (r=0.809) is for line of sight measured against global integration.

Table 1. Route C correlation (r) matrix.

ROUTE C	v-connec	sky	floor	sky/floor	road centre	line sight
logChoice	0.571	0.463	0.414	0.401	0.355	0.693
logChoice300	0.336	0.184	0.163	0.154	0.358	0.425
Int	0.777	0.762	0.616	0.720	0.552	0.809
Int500	0.734	0.814	0.528	0.796	0.232	0.629
Int100	0.387	0.624	0.313	0.631	0.028	0.200

3.2 Route L

Route L, the route with the most numerous number of locations (43), is also the route with the strongest correlations (see table 2). With a few exceptions, there are strong correlations across the matrix; the strongest correlation is between line of sight and global integration (r=0.843).

Table 2. Route L correlation (r) matrix.

ROUTE L	v-connec	sky	floor	sky/floor	road centre	line sight
logChoice	0.627	0.666	0.472	0.576	0.530	0.674
logChoice300	0.610	0.516	0.523	0.357	0.456	0.666
Int	0.750	0.709	0.694	0.550	0.817	0.843
Int500	0.751	0.744	0.696	0.563	0.820	0.823
Int100	0.612	0.781	0.585*	0.600	0.720	0.616

* p = 0.273

Route StP

Route StP, the route with the fewest number of locations (26), is characterized by a slight slope. The vertical displacement between the initial and final locations along route StP is almost 7m in contrast to a vertical displacement of around 2m for routes C and L. It is probable that the negative correlations within the correlation matrix are due to this, given that they occur principally with the sky, floor and skyfloor variables where vertical displacement is a crucial factor. In addition, there are two outliers that can be considered anomalies when measuring the line of sight variable; locations 1 and 2 have a depth of view of more than 560m, far exceeding the values of the other variables (see figure 9).

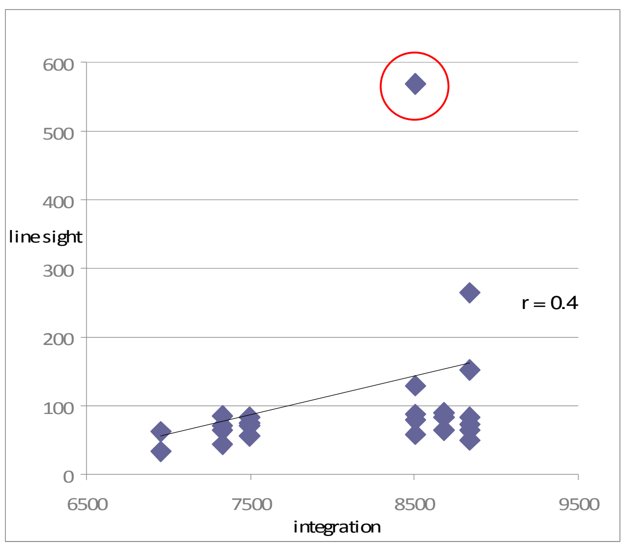

Fig. 9. Scatterplot of Route StP: global integration – line of sight.

The correlation matrix for route StP is not as strong as for the other routes; unlike routes C and L, there are no correlations of r > 0.6. One possible explanation is that it is the reduced number of locations (26) compared with the route L with the strongest correlation matrix which has 43 locations, although this hypothesis needs to be tested further. The variable with the strongest correlations across the space syntax measures is line of sight.

Table 3. Route StP correlation (r) matrix.

ROUTE StP	v-connec	sky	floor	sky/floor	road centre	Line sight (excl. StP1 and StP2)
logChoice	-0.073	0.231	0.234	0.234	0.309	0.330
logChoice300	-0.026	0.156	0.154	0.172	0.324	0.479
Int	0.018	-0.018	-0.059	0.041	0.275	0.400
Int500	0.363	-0.409	-0.414	-0.303	0.305	0.389
Int100	0.396	-0.506	-0.528*	-0.390	0.297	0.363

* p = 0.487

3.3 All Routes

A correlation was sought for all 107 data points put together irrespective of route. The two anomalies in the line of sight variable for route StP were excluded. The correlation matrix presents some strong correlations, although it is not as strong as the individual matrices for routes C and L. Global integration is the space syntax measure with the strongest correlations, and both v-connectivity and line of sight are shown to be relevant visual variables.

Table 4. Correlation (r) matrix for all routes.

ALL ROUTES	v-connec	sky	floor	sky/floor	road centre	line sight (excl. StP1 & StP2)
logChoice	0.492	0.424	0.398	0.395	0.420	0.612
logChoice300	0.373	0.293	0.324	0.252	0.382	0.453
Int	0.681	0.462	0.546	0.431	0.637	0.769
Int500	0.664	0.268	0.374	0.263	0.535	0.687
Int100	0.507	0.270	0.313	0.276	0.424	0.366

4 Discussion

The aim of the study was to identify the visual properties of spatial configuration. The study shows strong correlations across the six variables and the space syntax measures. This suggests that there are visual properties to the 2D geometry of the environment. Whether these are variables that are important during navigation will be the focus of a subsequent behavioral study. To fully understand the importance of these variables on the individual, specific types of data need to be collected. One avenue would be to track the gaze bias, where issues of saliency within the photographs and visual attention could be addressed; one such experiment is currently underway. Another avenue would be to track the hippocampal activity in an fMRI scanner (see [33] and [34]).

The new methodology, using 360 photographs to represent the experience of walking along a route, proved useful in fulfilling the aims of the study. Of the six variables, line of sight proved to be the most promising. This suggests that one factor already present in the space syntax model that could be relevant when trying to incorporate elements relevant to the individual would be depth of view. Furthermore there is evidence to suggest that line of sight is important during navigation (see [29], [30], [31] and [18]); this will be further tested in the subsequent stages of this research. Visual connectivity was a useful measure, correlating strongly in routes C, L and when considering all locations together. In particular, the correlations with global space syntax measures appeared to be stronger than for local measures, suggesting that visual connectivity picks up on a global element of the space syntax model. There is some evidence to suggest that the permeability measure is interrelated with the accessibility and connectivity measure even when looking solely at the visual properties of a scene. This would correspond with some of the tenets of space syntax theory [2]. The relation between these three measures is based on the correlations for the global space syntax measures in all routes, although to a lesser extent in route StP, and is a hypothesis that requires further evidence. The percentage of sky area was a useful variable to some extent, and its potential to represent 3D aspects of the environment renders it interesting for future research, taking into account the indications from [35]. A future research path could include many more 3D-related variables in an attempt to relate the space syntax model also to the third dimension. The percentage of sky and floor areas revealed some strong correlations, but should be refined as variables if they are used in subsequent studies, to allow for a standardized method to control for vertical displacement. One point upon which to base these two measures would be street width, a relevant visual variable in itself that relates closely to the 2D geometry of the environment. In addition, another interesting variable that could produce interesting results would be the angle of incidence of each connecting street. The ratio between the sky and floor areas proved to be a less critical variable. The chosen space syntax measures adequately represented the space syntax model, and global integration correlated very strongly with many of the variables across the routes. In the majority of cases the correlations with integration outperformed those with choice.

It is important for the space syntax model to be relevant at the level of the individual in order for it to be able to progress into a predictive model for wayfinding behaviour. It is hoped that the research that develops from the study presented in this paper will be able to contribute to that goal.

Acknowledgments. The author wishes to thank Dr Ruth Conroy Dalton for her guidance and comments.

5 Appendix: Space syntax images

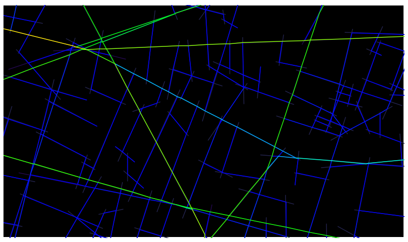

Figure 1: Bank - choice

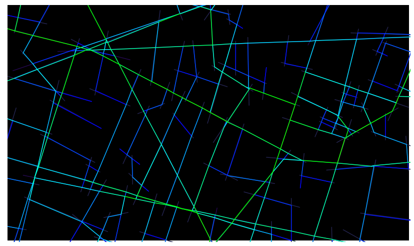

Figure 2: Bank - choice R300

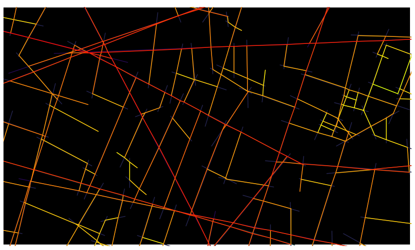

Figure 3: Bank – integration

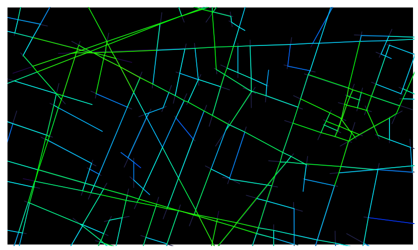

Figure 4: Bank - integration R100

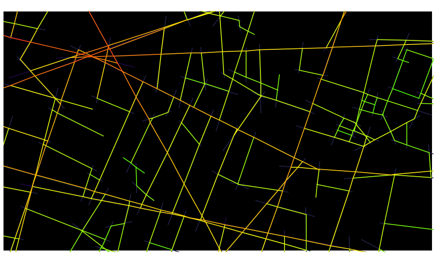

Figure 5: Bank - integration R500

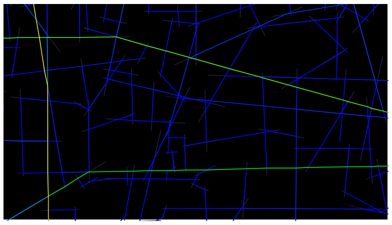

Figure 6: StP - choice

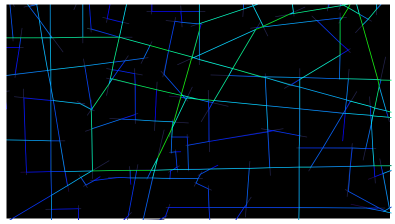

Figure 7: StP - choice R300

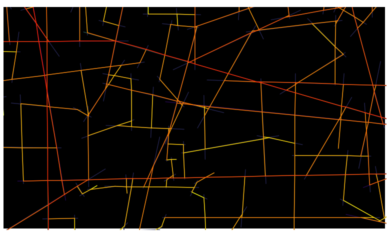

Figure 8: StP - integration

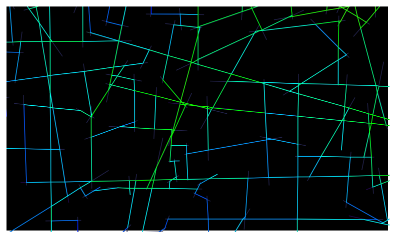

Figure 9: StP - integration R100

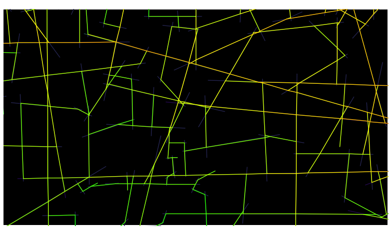

Figure 10: StP - integration R500

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Using formal descriptions of environments to understand wayfinding behaviors: The differences between methods[1]

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Abstract. The purpose of this study is to review popular methods that have been developed to provide formal descriptions of environments and to point out their contributions in understanding human wayfinding behaviors. A theoretical frame is developed based on the perceived elements of built environments (edges, nodes, districts, boundaries, and landmarks) and the legibility of environments (layout complexity, visual access, and differentiation of environments). Each method is reviewed based on the same frame individually. Particularly two widely used methods (Inter connection density and Visibility graph analysis) are reviewed in details and validated through a preliminary behavioral experiment. Later, a table summarizing these methods of formal descriptions based on the theoretical frame. At the end, ways to enhance formal descriptions of providing a better account of environment and its legibility are suggested.

Keywords: formal description, space syntax, wayfinding, legibility

1 Introduction

A person's wayfinding behaviors differ by environments. This is because wayfinding is an interactive process between both the human body and the environment (Allen, 1999). This indicates that not only individual differences characterized by persons' familiarity, age, sex, or spatial abilities, but also the characteristics of environment play an influencing role on human wayfinding behaviors. Efforts from multiple disciplines such as architecture, urban planning, behavioral geography, environmental

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psychology and computer science are made to understand the role of physical environments play on wayfinding. That is, how to formally describe the characteristics of environments and relate them to human wayfinding behaviors.

Legibility of built environments is used to describe how differently the environment contribute to the development of mental representations and subsequent wayfinding behaviors (Lynch, 1960). O'Neill (1991, p. 259) summarized legibility of a built environment as "the degree to which the designed features of the environment aid people in creating an effective[…]cognitive map of the spatial relationships within a building, and the subsequent ease of wayfinding within the environment." Weisman (1981) proposed the model of legibility by taking into account the following environmental characteristics: differentiation of environment, degree of visual access, complexity of spatial layout, and signage. Gärling*, et al.*, suggested that signage is considered as an independent influential factor (Gärling*, et al.*, 1986). The elements of environments in mental representations include paths, edges, districts, nodes, and landmarks (Lynch, 1960). The components of the elements and legibility are also shown in Figure 1. In addition, the composition of the characteristics of environment and human, as well as the methods to assess these characteristics are also shown in this Figure.

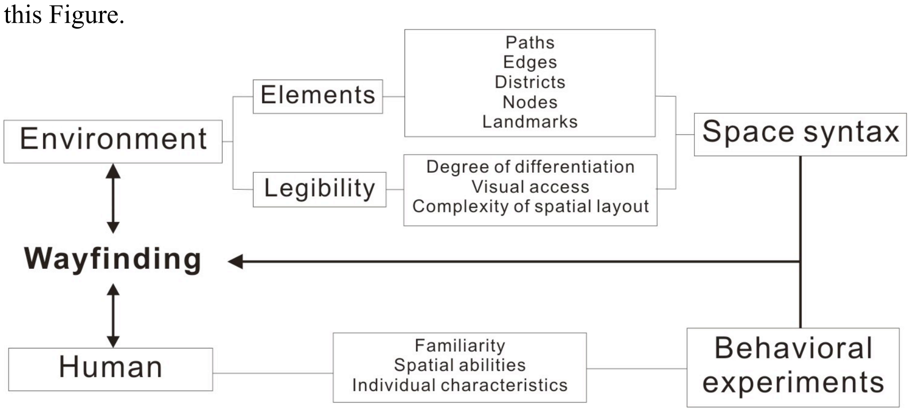

Fig. 1. Relationship between environment and human, and the workflow of current study.

In short, the main purpose of this paper is to review popular methods that have been used to formally describe physical environments. Two major methods, Inter connection density (ICD) and Visibility graph analysis (VGA), will be reviewed first and then validated in behavioral experiments. The review of each method is based on a theoretical frame consisting of the elements of the environment (Lynch, 1960) and legibility of environment (Weisman, 1981). A summarizing table of all reviewed methods of formal descriptions will be given at the end based on the theoretical frame.

2 Formal descriptions of built environments

The term space syntax has been widely used in multiple disciplines referring to the formal way of quantifying built environments (Bafna, 2003). However, some methods were introduced before for the same purpose of formally describing environments. Hence we use the term formal descriptions to reflect the important use of related methods to quantify elements of environment and to provide insights on understanding human wayfinding behaviors.

In this section, methods of formal descriptions will be discussed in their relations to the understanding of wayfinding behaviors. Specifically, two widely used methods are introduced first: ICD and VGA. These two methods are those which were validated in the behavioral experiments. Second, more related methods of formal descriptions are reviewed individually based on the theoretical framework. Examples of using certain methods will be given in most cases to illustrate their uses.

2.1 Inter Connection Density (ICD)

The concept of ICD is to calculate the average number of connections of all decision points that an environment possesses (O'Neill, 1991). Decision points and the topological connections between them in a built environment are considered to be an important factor of indicating the ease that people can develop mental representations. First, intersections which have more than two options of directional changes in an environment are considered as nodes. Second, the number of connections to other decision points from each node is considered as the connectivity. Third, the main product of the ICD is the value showing the mean connectivity of nodes in an environment. An example of the drawn connectivity between nodes and the calculated ICD is shown in Figure 2.

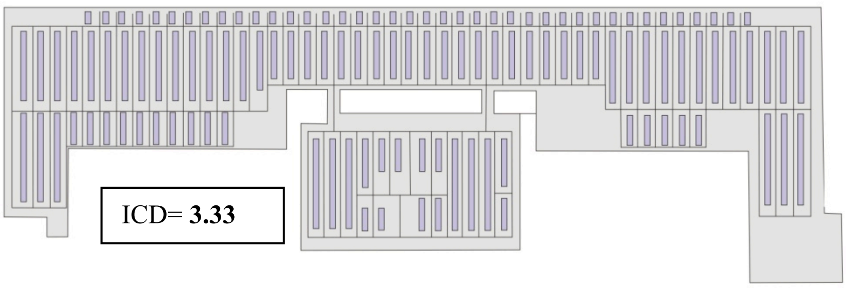

Fig. 2. Connection of nodes and ICD of a library area on the authors' campus. The lines in the map represent all connecting paths and the value in the box is the ICD.

The purpose of using ICD is to verify whether the complexity of topological configurations influences the legibility of an environment. O'Neil (1991) suggested that the legibility of an environment mediated the development of mental representations, which subsequently influence wayfinding behaviors. According to elements of environments represented in mental representations (Lynch, 1960), nodes and paths were clearly stated as the elements in the method of ICD.

ICD is effective in describing topological complexity of a floor plan. It has been suggested that topological complexity of an environment played an important role on the ease of developing mental representations. Because topological relationship is the knowledge acquired by wayfinders before they perceive other information such as distance or direction (O'Neill, 1991). Hence it could be considered as an important evaluation for estimating wayfinding behaviors of novices in an environment. However, it has been pointed out that the development of mental representations is not only affected by the topological complexities but also geometric complexity. Studies suggested that floors can have the same topological complexity but different geometric complexity leading to differences of acquisition of spatial knowledge (Haq & Zimring, 2003) and wayfinding performances (Werner & Schindler, 2004). In short, the effectiveness of using ICD should be carefully justified because an environment with extremely irregular floor plans can result in dramatic differences in geometric complexity, which is not reflected in ICD.

It is important to point out that one aspect of the environment was neglected in the original method of ICD. In this method, library floors were used as the experimental sites to testify this measure. The rationale of choosing nodes for ICD was the decision points in the environment that only main hall ways were considered. However, in a library setting the aisle shaped by two nearby stacks forms a path for wayfinders. This aspect was neglected in the original method. Hence we suggest nodes and connections formed by the book stacks should be considered in calculating the ICD for libraries. In the example of measuring ICD of a library at the Penn State campus, all possible paths in the library area are considered as shown in Figure 2.

In sum, ICD considers locations where wayfinding decisions are made and their connections to other locations. It indicates the average connectivity formed by the number of nodes and the connections between these nodes. Its original purpose is to correlate this aspect of the built environment with ease of developing cognitive map. It has also been used to assess the design of built environment for evacuation (Ünlü*, et al.*, 2005). Generally, the topological complexity represented in ICD is a key component of the layout complexity that influences the legibility. But when using ICD to assess a built environment, the geometry of the environment should be evaluated first especially when multiple environments are being assessed. Only when environments possess a similar geometrical complexity, ICD can be used effectively to convey the topological complexity underlying the built environment. In addition if a research purpose is to evaluate the legibility of a built environment, supplemental methods should be used to address the other two aspects.

2.2 Visibility Graph Analysis (VGA) and Isovists

VGA as well as isovists, represents environment with regards to the visual areas a wayfinder can see at given locations. Isovist is the concept introduced before VGA. The concept of visibility originates from the perspective of human visual perception.

Benedikt (1979) considered an isovist as the shape of space that a person can perceive in his/her vision at a location in the environment. Isovists are then determined by the boundaries of the environment and the vision of people at a given location. Studies have suggested strong relationships between isovists and spatial behaviors (Meilinger, *et al.*, 2009; Wiener & Franz, 2005). Most isovists were implemented to take into consideration only one location at a time using the visual convex shaped by the boundaries and vision to represent the areas a person can see. Later improvement includes direction-specific isovists (Meilinger*, et al.*, 2009) which restrict the scope of visibility to only facing direction. The method VGA (Turner*, et al.*, 2001) extended the representation of local isovists to global representations. Different from the isovists, VGA represents all visible locations on a global level. One example of using VGA to assess the same library area as used in earlier sections is given in Figure 3.

The most important role VGA plays is showing locations of different degrees of visibility (Penn, 2003). As visual access is identified as a critical factor of affecting the legibility of environments, the difficulty of acquiring spatial knowledge at locations of low visibility will likely be greater. Wiener and Franz (2005) tested participants to find the best overview place or hiding place in a building. Because either the best overview place or hiding place was directly related to visibility, isovists seem effective in predicting participants' preferences for those places. However, cognitive processes underlying wayfinding do not only relate to visual access but also locations of decisions points (Davies*, et al.*, 2006).

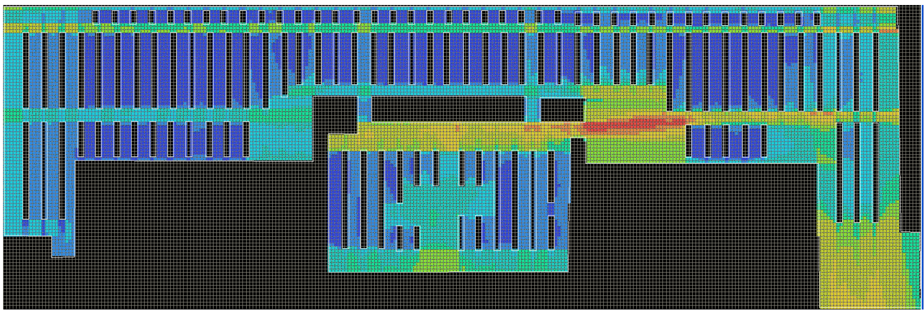

Fig. 3. Visibility Graph Analysis of the same library floor. Areas in red and orange represent good visibility and areas in blue and purple represent poor visibility.

VGA and isovists account for the visual access of legibility in built environments. Based on visible spaces in the environment, the polygon formed by the restriction of environment consists of several elements of the environment in mental representations. First, areas where vision can reach represent the districts that this person can access. Second, the restrictions provided by the walls which influence the visibility can be treated as boundaries. VGA have been used in studies to verify the relationship between wayfinding behaviors and visual access of environment (Hölscher & Brösamle, 2007).

The correlation between isovists and locations where decision making occurs has been attempted to be established. However studies showed the difficulty of correlating isovists and locations in environment where orientation is performed. Davies *et al.* (2006) tested the use of isovists and a pictures-and-maps experiment to evaluate wayfinders' performances orientation. The results showed the shortfalls of using isovists to predict orientation performances. Instead, signs were more favored to be selected to indicate locations for orientation.

In sum, VGA and isovists provide effective assessment of boundaries and areas of a built environment to reflect its legibility. They represent the visual access that a person can obtain at locations in environment. However, only visual access is represented in this method. When using isovists to examine wayfinding behaviors, additional measures should be considered to address the aspects such orientation and route choice in wayfinding.

2.3 Axial maps

The previous two methods are widely used to formally describe environments. From this section, more methods of formal descriptions will be reviewed with fewer details. The method reviewed here is axial maps. An axial map uses fewest lines to present the continuous structure of networks in a built environment by constructing the fewest conceptual partitions of the environment (Hillier & Hanson, 1984). Originally, the purpose of using axial maps is to understand the urban morphology and its relation to social movement. Lines in an axial map are named axial lines to represent the longest lines among continuous structures of a network. They were used as a method to represent street networks in a less complex way. These lines could be treated as paths in wayfinding, even though they are actually conceptual representation of connectivity in axial maps. Algorithms have been developed to create axial maps of built environments (Turner*, et al.*, 2005). Generally, out of the five elements of built environments, paths are the elements of the environment represented in axial maps. Figure 4 shows an axial map of the library area on the authors' campus.

In terms of legibility, the aspect that axial maps represent is related to the complexity of spatial layout. At the same time, other aspects of environment legibility are not represented. One application of axial maps is to correlate the axial lines with movement flows in built environments. However, the correlations of movement patterns are all on an overall observation instead of individual counts. It has been pointed out that it is inapplicable to correlate the accessibility to individual movement patterns and an understanding of environments (Desyllas & Duxbury, 2001; Tomko*, et al.*, 2008). This leaves the question of how to relate individual behaviors to the method of axial maps.

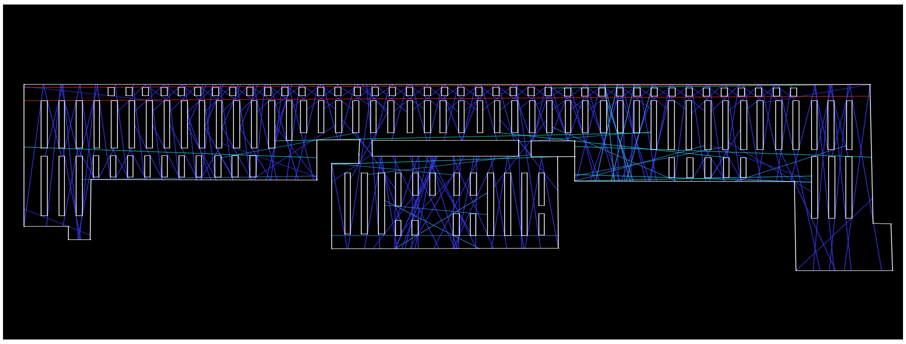

Fig. 4. Axial map of an area in the Penn State library. Axial lines in red colors indicate higher connectivity, while lines in blue or green colors indicate lower connectivity.

In sum, axial maps are effective to represent paths that are accessible to wayfinders. However, the knowledge of routes consists of successive sequences of anchoring points connected by experienced paths of movement (Siegel & White, 1975). These anchoring points are ideally characterized by landmarks. However, those anchoring points are not represented in axial maps. Therefore how those anchoring points contribute to the understanding of cognitive map development is unlikely to be reflected in axial maps. In other aspects, an effective utilization of axial maps is in assessing the hierarchy of street networks in mental representations. Tomko *et al.* (2008) used both axial maps and people's spatial experiences about street networks in urban areas and suggested the outcome as input to generate hierarchical route directions.

2.4 Point-based measure

Point-based measure takes paths and nodes of an environment into its consideration. It was introduced by Jiang and Claramunt (2002) as an enhancement to the method of axial maps (Hillier & Hanson, 1984). One improvement of this method is its consideration of nodes in addition to only lines in axial maps. First of all, in addition to the connectivity represented by axial maps, the point-based measure provides the value of connectivity to each path produced in the output. Second, the derivation of axial lines is based on the convex partition of a space such that the space is represented with the fewest number of convexes hence the axial map has the fewest axial lines. However, the point-based measure directly uses paths and nodes in the environment to represent the connectivity. Overall, the point-based measure is an attempt to improve the axial maps method. Although the representation of point-based measure seems similar to the axial maps, they originate from different theoretical and computational approaches. Figure 5 shows the output of the same library area using the tool Axwoman (Jiang & Liu, 2009) developed according to the point-based measure.

Point-based measure uses paths and intersections of the environment as nodes. The intersections are important locations where wayfinding decisions are made and paths are accessible to wayfinders. The legibility of environment reflected by the point-based measure is the complexity of spatial layout. Although the original purpose of using a point-based measure is to support urban morphological studies, its theoretical basis is similar to the environmental knowledge that a wayfinder would acquire (i.e. route and landmark knowledge). Using paths and nodes as elements in assessing the built environment provide important information to investigate the relationship between environment and wayfinding behaviors.

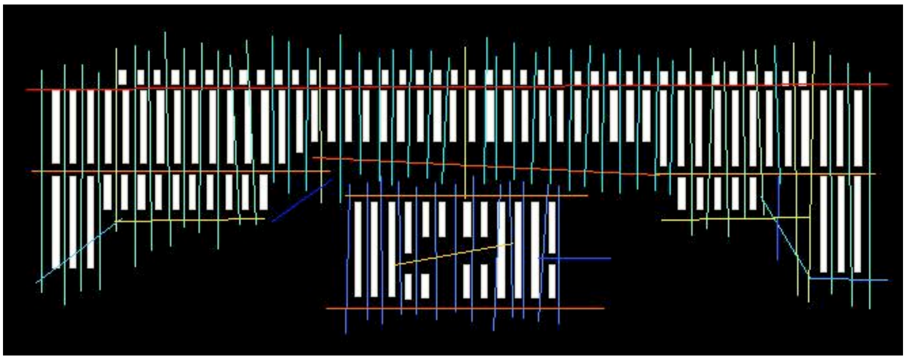

Fig. 5. Output of the point-based measure of an area in Penn State library. Lines in red or yellow colors indicate higher connectivity while lines in blue or green colors indicate lower connectivity.

2.5 Integrated methods

One solution to overcome the limitation of formal descriptions is to integrate multiple methods to address different characteristics of the environment for a fuller account of legibility. In this section, several methods that integrate different methods of formal descriptions will be introduced and their advantages and potential issues are discussed.

Using Hiller *et al.*'s (1987) axial maps as the core concept, Peponis *et al.* (1990) introduced the method *search structure* to provide formal descriptions of built environments. The biggest distinction of the search structure from the method of axial maps is that search structure additionally considered integration value and nodes of choice in this method. First, the axial lines were obtained through axial maps. Second, the integration value was represented by a graph showing the number of changes of direction or a space in relation to all other spaces. Third, the intersections represent the nodes of choice. Generally, the connectivity in the environment is revealed by axial lines. This method not only adopted popular space syntax measure but also used additional measures to describe a building's layout. Similarly, the nodes of choice expressed the same idea of ICD (O'Neill, 1991).

Hölscher *et al.* (2006) integrated both axial maps and VGA into formal descriptions of a built environment. In their study, the analysis of the axial map is carried out as the first step. A general structure of the building is obtained through this analysis. In the last step, the properties of the space are linked to behavioral observation to evaluate the correlation between the spatial properties and spatial behaviors. According to legibility of the environment, the axial maps provide information on layout complexity while VGA provide insight on visual access. Even though the other aspect of legibility—differentiation of environment—was not addressed, this study demonstrate the possibility of using multiple methods of formal descriptions in behavioral studies.

Ünlü *et al*. (2005) used different methods in their *multi-factor framework* for designing and evaluating evacuation plans in a large built environment. Several additional characteristics of the environment were considered influential factors. For example, the integration value of the floor plan, the visibility, and distance between destination and other locations in the environment were considered in the assessment. Formal descriptions used in this study address the visual access and connectivity of the environment. However, the assessment of the built environment in this study was done at local scales that individual decision points were evaluated separately. Method such as VGA can be used to supplement this analysis to provide additional information on this environment. In addition, differentiation of environment is also neglected in this study.

Tawfik *et al.*(2007) used a *multi-criteria analysis* to evaluate built floor plans. This method categorizes floor plan based on three criteria including travel criterion, comfort criterion, and quality criterion. Although the quality criterion addressed aesthetics and safety, formal descriptions were used in travel criterion and comfort criterion. It supports the possibility of using different methods to carry out formal descriptions of built environment.

2.6 Other methods

Before space syntax has been popularly used, other methods have been introduced way earlier to address the relationship between human cognition and built environment. Due to the introduction at early times, these methods have been either improved or replaced. Hence only brief descriptions of these methods are given in this section.

Pathway configuration and landmarks were suggested as important properties related to environmental cognition by Evans *et al*. (1984). The pathway configuration was categorized as non-grid or grid path and landmarks were categorized as internal or external landmarks depending on whether they indicate specific locations or general directions respectively. However, the verification of this method was executed through simulations on computer. It seems that the correlation identified between physical environment and cognition was actually the correlation of the simulations and environmental cognition. The authors argue that real environments cannot provide accurate information on environmental cognition and hence used computer simulations. As most human wayfinding behaviors occur in the actual physical spaces, using computer simulations might lead to biased results to support the correlation between physical environments and wayfinding behaviors.

One possible development to use this method in practice is the adoption of this model on real physical environment in further studies.

The *objective environment measure* was introduced by Gopal *et al*. (1989) as a different method to describe the environment. Based on Lynch's (1960) elements of city in mental representations, this model was supplemented by a subjective representation of environment as comparison between environmental properties and the mental representations of environment. There were two properties of environments considered in this objective environment model: landmarks and paths. Specifically, landmarks were represented by locations and their associated sets of objects (e.g. houses and their surroundings) and decision making locations. Paths were represented by networks of streets. Overall, this model is well supplemented by the subjective measurement of the representations of the environment. It contributes to the verification of the objective model. However, this objective environment model could consider more characteristics of the environment. As landmark and path play important roles of influencing the development of mental representation of environment, other characteristic such as the configuration resulted from the structure of the environment can have influences. That is to say, supplementary method of objective measurement should be considered to improve the full account of the environmental characteristics.

3 Behavioral validation

An exploratory experiment was carried out to compare the differences of two methods of formal descriptions and correlations with wayfinding behaviors. Out of all 8 participants, 4 had limited experiences in the library areas and the other 4 had never been to the library before the experiment. Each participant was asked to locate 2 books in each of three library area (Paterno Library, Central Stacks, and West Pattee). At the end of finding both books in each area, they were asked to give horizontal directional estimations to the same main reference desk. The whole procedure of locating books were videotaped and further digitized to obtain the distance and time each participant took in each task.

Two methods of formal descriptions were chosen to demonstrate the differences that formal descriptions reveal. VGA and ICD address distinct characteristics of the environment: VGA mainly addresses on the visual access of the environment, and the ICD emphasized the layout complexity which is represented by the density of nodes in the environment. Results of using these two methods to formally describe all three libraries are shown in Figure 6. It is obvious to notice that Central Stacks produces the lowest visibility and the highest ICD. Paterno Library has the second highest ICD and high visibility. West Pattee has the lowest ICD but also very high visibility.

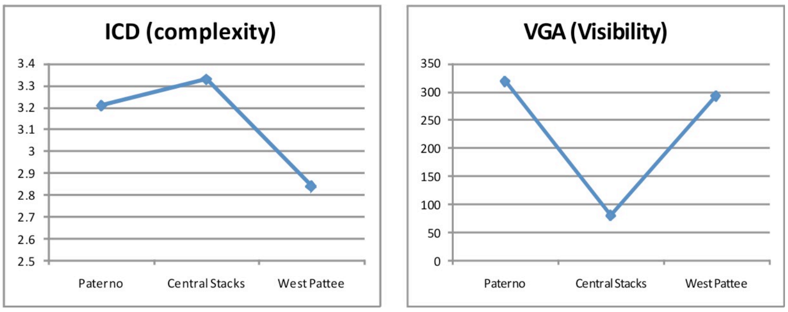

Fig. 6. Output of ICD and VGA of all three library areas

The wayfinding performances of participant were categorized by group depending on their familiarity of the environments. Measures include the time that participants spent on locating books in each area, additional distances walked by comparing to the simplest route, and errors in the directional estimations. These results are shown in Figure 7.

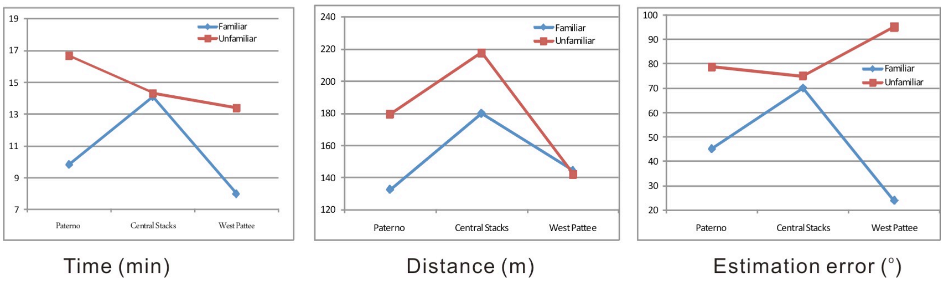

Fig. 7. Wayfinding performances and directional estimations of participants by group in each library area

The results of formal descripts seems to be related to different aspects of wayfinding behaviors. At first, the values ICD produced seem correlated positively with the time participants spent in each area. Specifically, regardless of familiarity, participants spent least time in the area whose ICD is the lowest. Second, VGA results seem correlated positively with the distances that participants additional walked in each library area. For example, the longest additional distances were walked by participants in Central Stacks regardless their familiarity. Third, as a reflection of the development of mental representations, the directional estimations do not represent a simple relationship with either result of formal descriptions. The directional estimations made by group who had limited familiarity are correlated negatively with the results VGA produced. That is to say, the higher VGA an environment possesses, the lower estimation errors participants make. However, to the group who has no familarity to the library, the estimation error is correlated negatively with ICD.

Particularly, the area with highest ICD is related to the lowest error of estimation while the lowest ICD is related to the highest error of estimation.

It is noticable that layout complexity and wayfinder's familiarity seem to have different weights on influencing wayfinding behaviors. The time spent and the distances walked by participants were longer in the Central Stacks compared to the other two library areas. The pointing errors also imply that the Central Stacks did have more difficulty to participants on estimating their spatial orientation. The layout complexity of the Central Stacks played a much more important role than participants' familiarity. However, in the Paterno Library and West Pattee where the layout complexity was relatively low, the familiarity of the environment plays a more important role than the layout complexity on directional estimation. This finding is on the contrary to earlier finding that familiarity was suggested to play a more important role on wayfinding performance than layout complexity (O'Neill, 1992). Further assessments are necessary to reveal the different influences of layout complexity and familiarity on wayfinding performances.

In sum, as wayfinding is the behavior human interact with the environment. It is inevitable to notice that both individual familiarity and environments play roles on impacting wayfinding. Through the observations of the selected formal descriptions of environments and a prelimenary wayfinding experiment, the differences between methods are presented. It is important to acknowledge the advantage each method of formal descriptions provide and the limit that each method has for the further imporovement on these methods.

4 Conclusion

The main aspect this review addresses is the elements and legibility of built environments represented in formal descriptions and their correlations with wayfinding behaviors. Elements of built environments represented in mental representations were used in those methods of formal descriptions in order to indicate the legibility of environment. A summary of the evaluation of all aforementioned formal descriptions is presented in Table 1. Although the preliminary experiment does not include a large pool of participants, the findings presented in our study does show some interesting patterns and worth further verifications.

One finding noticeable from methods summarized above is that the differentiation of environment was not frequently addressed. Since the effectiveness of landmarks in human wayfinding behaviors has been favorably suggested to differentiate environment and give wayfinding directions (Raubal & Winter, 2002), consideration of landmarks cannot be eliminated for the fuller account of legibility. Therefore assessing characteristics of landmarks will not only benefit a more comprehensive understanding of legibility of environments but also contribute to the design of wayfinding aids. Visual, structural and semantic properties are considered essential components of landmarks (Sorrows & Hirtle, 1999). These three properties have been further used in studies (i.e. Klippel & Winter, 2005; Raubal & Winter, 2002) to carry out saliency measurement of landmarks. Approach from different perspective also suggests the measurement of saliency of landmarks. Caduff and Timpf (2008) suggested a framework from cognitive perspective. Cognitive saliency, perceptual saliency, and contextual saliency were used as the three aspects of landmark saliency. This framework provided a new lens of looking at landmark saliency to assess environments. However, as this framework is still on a conceptual level, imperial justification is necessary to verify its feasibility in interpreting landmark saliency through the new lens.

Table 1. Summary of elements of environment and legibility addressed by formal description

Formal description	**Elements of environment**					**Legibility**		
	Edges	Nodes	Districts	Boundaries	Landmarks	Visual access	Layout complexity	Differentiation
Axial map	√						√	
ICD		√					√	
VGA			√	√		√		
Multi- factor framework	√	√				√	√	
Multi-criteria analysis	√	√				√	√	
Point-based measure	√	√				√	√	
Search structure	√	√					√	
Path configuration and landmarks	√				√			√
Objective environment measure	√	√						√

It is important to acknowledge that although the aforementioned formal descriptions do not cover all characteristics of environmental elements and legibility, they serve their roles in specific applications. As used in the exploratory study, different methods seem to have specific correlation with wayfinding performances. Supplementing existing formal descriptions seems to be a feasible way to conduct formal descriptions of environment for wayfinding research. The improvement of measuring landmark saliency serves an important role to provide insights on differentiating environments. An integrated method of formal descriptions addressing these three characteristics of legibility is necessary to provide fuller account of environmental characteristics that impact wayfinding in built environment.

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