Abstract

It has been long-known in cognitive psychology that geometric and configurational features of the environment influence human orientation and navigation (e.g., Weisman, 1981; Gärling et al., 1983). Yet proper analytic characterisation of environmental features has generally been elusive in these studies. More recently, space syntax methods have been adopted to capture environmental determiners of individual human navigation decisions (Peponis et al., 1990; Haq & Zimring, 2003; Conroy Dalton, 2003). Our study extends this approach by introducing route-based space syntax measures that capture the interplay of spatial features of a building with cognitive properties (level of prior knowledge) of its users. For this purpose we reanalyse an experiment on wayfinding in a complex multi-level conference centre (Hölscher et al., 2005). The empirical study compared the performance of experienced and inexperienced participants in a set of wayfinding tasks, identifying specific strategies for vertical navigation. Inexperienced participants predominantly rely on a central-point strategy, while experienced ones have more accurate knowledge and plan more effectively. They prefer a memory-efficient “floor strategy” of swift movement to the destination floor. The building and its vertical connections were segmented into cognitively plausible subsections corresponding to decision points in the corridor network. For each path segment we computed VGA-based average connectivity, integration and step depth (to target location) with Depthmap (Turner, 2004). Movement trajectories of each participant were translated to a string of visited segments for each task. Route-specific space syntax measures were computed by aggregating the values of all segments along each string, based on both maximum and mean values. Step depth between start and goal location proved to be an excellent predictor of general difficulty of a wayfinding task, since we find significant correlations (r=.77 to .87) with 5 of 6 behavioural performance variables. But more importantly, the route-based measures reveal distinct, statistically reliable differences between experienced and novice users of the building. The experienced participants showed lower mean step depth to goal along their paths, thus avoiding unnecessary route segments. By contrast, the routes chosen by novice users had significantly higher values on mean and max connectivity as well as mean and max integration. Having less precise knowledge about the setting, they rely more on locally visible information and relatively familiar building parts like main corridors and the entrance area, as reflected in their central point strategy. Overall, our relatively simple route-based measures capture important behavioural differences between users and ultimately tie them to differences in spatial knowledge and cognitive strategies.
Introduction

Finding one’s way around public buildings such as airports, hospitals, offices, or university buildings often proves to be a tedious and frustrating task. In the present study we aim to make progress towards linking architectural design and human spatial cognition research, especially understanding the relationship of spatial features in the environment on the one hand and people’s cognitive strategies and path choice preferences on the other.

Hölscher et al. (2005, in press) have presented an empirical investigation of wayfinding behavior in a complex multi-level setting, a conference centre. They were able to show distinct behavioural differences between study participant who had considerable prior experience with the building compared to inexperienced visitors and these differences could be tied to different navigation strategies employed depending on the level of familiarity with the setting. In the present paper we will re-analyze the 2005 study based on a set of space syntax analyses of the setting. After briefly reviewing relevant literature on human wayfinding in built environments we first describe the setting and the experimental procedures of Hölscher et al. (2005) as a background for our investigation. This is followed by a formal analysis of the building with Visibility Graph Analysis (VGA). On this basis, we introduce a set of newly-derived measures to capture properties of individually travelled routes in a building. The wayfinding patterns of the study participants are related to route-specific measures based on connectivity, integration and step depth to uncover task effects as well as group differences regarding familiarity with the building. Limitations of the approach and opportunities for future research are covered in the discussion section.

The Challenge of Wayfinding

Best’s (1970) pioneering study on indoor navigation was the first to identify fundamental aspects of a building’s route network, like choice points, directional changes and distances as relevant predictors of wayfinding difficulties in complex buildings. Weisman’s (1981) identifies four general classes of environmental variables that shape wayfinding situations: visual access, the degree of architectural differentiation, the use of signs and room numbers, and floorplan configuration.

Another essential point seems to be the familiarity with the building. Gärling et al. (1983) point out that familiarity with a building has substantial impact on wayfinding performance. So does visual access within the building: If large parts of the building are immediately visible and mutual intervisibility (vistas) connects the parts of the building, people have to rely less on stored spatial knowledge and can rely on information directly available in their field of vision. A disadvantage of these lines of research is that floorplan complexity and configuration as well as visual access have been defined rather informally in the literature discussed above (e.g., by subjective ratings). The concept of isovists (Benedikt, 1979) provides a much more precise mathematical framework for capturing local properties of visible spaces, which correspond with psychological measurements of environmental perception (Stamps, 2002). Space syntax (Hillier & Hanson, 1984) has introduced formalized, graph-based accounts of layout configurations into architectural analysis. Calculations based on these representations express the connective structure of rooms and circulation areas in a building and are strongly associated with route choices of hospital visitors both in unguided exploration and in directed search tasks wayfinding behavior (Peponis et al., 1990; Haq & Zimring, 2003). Yet research along this methodology is generally based on correlations of building layout and aggregate movement.
patterns, thus providing no immediate understanding of individual cognitive processes (Penn, 2003). Recently, Hillier and Iida (2005) have presented initial approaches to close this gap.

**Wayfinding Strategies for Multi-level Buildings**

Hölscher et al. (in press) provide an overview of the types of knowledge and the navigation strategies people employ in complex multi-level buildings. Depending on the degree of familiarity with the environment people use strategies of varying complexity: Novice users are most likely to follow a central point strategy of finding one’s way by sticking as much as possible to central, well-known parts of the building, even if this requires considerable detours. More complex strategies include the direction strategy of choosing routes that head towards the horizontal position of the goal as directly as possible (Hochmair & Frank, 2002; Conroy Dalton, 2003), irrespective of level-changes. By contrast, the floor strategy is to find one’s way to the floor of the destination first, irrespective of the horizontal position of the goal. People familiar with the building tend to rely on either of the two later strategies. Often they also have full knowledge about the building topology, making complete path planning feasible as an alternative to these heuristic strategies.

**Aims of the Present Study**

Navigation in multi-level buildings has received relatively little explicit attention in wayfinding cognition research as well as in the space syntax community. For both areas, handling the third dimension of stacked floors has been problematic. The navigation difficulties of the multi-level building in the present study clearly stem from vertical travel. Therefore it appears extremely relevant to carefully model the vertical connections in a set of space syntax analyses of the building.

Can Space Syntax account for wayfinding behavior? Wayfinding research has the distinct feature of providing data on purposeful travel between destinations of individual study participants with known behavioural goals. Therefore it appears necessary to capture the properties of path sequences rather than only looking at the spatial properties of single points or areas. We present initial attempts towards this end and test how route-based measures can account for the behavioural data.

**Wayfinding Experiment**

In this section we recapitulate the setting and experimental procedures of the original study by Hölscher et al. (2005) and describe additional procedures for the new analyses presented in the current paper.

**The Conference Centre**

The Heinrich-Lübke Haus, a conference centre, was built in 1970 in Güne, near Düsseldorf, Germany. The ground floor (level 0) of the multi-functional building illustrates the general characteristics and spatial organization of the layout (see Fig. 1). The basic structure consists of various simple geometrical elements that are arranged in a complex and multi-faceted architectural setting. This building is subdivided into a well-designed group of solids with void space between them. The building could be architecturally categorized as an "indoor city" (Uzzell, 1995) as it is composed of a small ensemble of units and a large public circulation area. Each group of solids implies various functions, e.g., the living quarters (C) have a quadratic design style and the communication area (D) a hexagonal design style. The main path of walking through the building is an axial one rather than a cyclical one.
Changing floors in the building reveals its spatial complexity and vertical impenetrability. As one can see in Figure 2 the layout of the hallways on every floor may appear to be locally one and the same for a casual user, but is actually different for each floor. For example, the configuration of the ground floor (level 0) and the basement (level -1) differs significantly. The consequences of this and related structural deficits of the building are discussed as usability hotspots in Brösamle, Hölscher & Vrachliotis (submitted).

Figure 1:
Plan view of ground floor: (A) main public entrance (B) entrance hall (C) living quarters (D) Commons - communication and conversation area (E) dining room (F) kitchen (G) coffee bar (H) lecture rooms

Figure 2:
The floors of the building with circulation areas; Starting points and goals of the navigation tasks are marked by numbers

Participants
Seven women and five men in their mid-twenties to mid-thirties were recruited for the wayfinding experiment during a cognitive science summer school. Six of them were familiar with the building. They had previously visited the one-week conference at least twice. The six participants unfamiliar with the building (three of them were women) visited the conference for the first time. Their sessions took place within the first three days after arrival.
Procedure

In this building, the participants' task was to find six locations. The participants were filmed with a camera and had to verbalise their thoughts. During the whole experiment participants were not allowed to use floor maps or ask other people for advice, but they were allowed to use signs or to look out of the window for orientation as long as they stayed inside. All participants received the tasks in the same order, as each destination point is the start location for the following task, making randomization unfeasible. Navigation tasks were as follows (see Fig. 2):

1. From outside the building, the participants were shown a wooden ‘anchor’ sculpture inside the living quarters. They had to find it from the main entrance without leaving the building again.
2. The goal was to find ‘room 308’.
3. Participants had to navigate to the bowling alley. It was located in the cellar of the building, where the locations for all leisure activities were to be found.
4. The ‘swimming pool’ could also be found there.
5. The participants had to navigate their way to the ‘lecture room number four’.
6. The final navigation task’s destination was the ‘billiard table’.

Data analysis

Performance measures: For each task, the shortest route as well as a list of reasonable route alternatives was determined beforehand. Reasonable routes are defined as neither containing cycles nor dead ends or obvious detours.

Navigation performance was measured with six variables: (1) time to complete the task, taken from the video; (2) stops; (3) getting lost, i.e., number of times participants left a ‘reasonable route alternative’ and showed detour behavior; (4) distance covered; (5) distance covered divided by length of the shortest possible route. (This parameter expresses the proportion of superfluous way independent of task length. E.g., a value of 1.35 can be interpreted as walking 35% farther than necessary); (6) average speed.

Path choice sequences: Based on the video-recording of each session, the walked route for each participant and each task was hand-drawn into printed plans of the building. This was used to determine distances of routes and superfluous way after getting lost (see above) as well as the position & duration of stops. Coding was done by two independent raters. In addition to the data processing for the Hölscher et al. (2005) analysis, further coding was necessary: To relate the behavioural data with the Space Syntax analysis of the building, we performed a detailed coding of the individual routes each participant took in each task. The route network in the building was segmented as illustrated in figure 4. The segments represent cognitively plausible subsections of the corridor network and correspond to decision points in the route network. With this coding scheme, the sequence of path choices is translated into a string of visited segments for each task and each participant.

Architectural Analyses with VGA

Several Space Syntax techniques are available the formal architectural analysis of this setting. Compared to an analysis of axial lines (Hillier & Hanson, 1984), visibility graph analysis (VGA; cf. Turner et al., 2001) provides a more fine grained representation of architectural space. The visibility graph is based on a two dimensional

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grid of points which fills all open space to be considered. Two nodes are connected if and only if the corresponding locations in space are mutually visible. The Space Syntax software Depth Map (Turner, 2004) was used for the VGA analyses. The step depth between two locations $a$ and $b$ is defined as the number of edges on the shortest path between $a$ and $b$ in the visibility graph. This measure reflects the number of turns required to get from $a$ to $b$. Connectivity or degree of a node $n$ is a local measure which captures the amount of space directly visible from $n$. The global measure integration is a normalized version of the mean depth of a node $n$ to all other nodes in the system. Intuitively integration reflects the centrality of a node with respect to the whole graph. For details on these measures please refer to Turner (2004; Turner et al., 2001).

We have identified the vertical structure of the building as a crucial factor in understanding its behavioural consequences. Since Depth Map supports two-dimensional visibility graphs only, the analysis is based on separate floor plans for each building level. Vertical interconnections in the staircases were modelled by manual connections to ‘widgets’ representing the staircases (for detailed descriptions of this procedure, e.g., avoiding doubled spaces, see Brösamle, Hölscher & Vrachliotis (submitted). The vertical connections were modelled so that the visual step depth between floors increases with the number of levels to traverse. A smaller set of steps (covering ca. 120 cm vertical height difference; within-level) in the main corridor towards living quarter was bridged with a corresponding widget area, as well. The results of the standard VGA analysis of the building are documented for connectivity and integration in Figure 3.

**Figure 3:**
Navigational Space

*Visibility Graph Analysis & Behavior Sequence Data*

As described before, participants’ trajectories were recorded in terms of sequences of visited building segments. To relate participants’ routes to different spatial measures of the architectural analysis, each behavior sequence was evaluated based on average syntax values of the visited segments.

The first step of the calculation is to determine the average connectivity and integration values for each building segment, based
on the VGA values of the points in the respective segment. In the same way, the step depth of a segment was calculated by averaging the step depth of the points in the segment to the destination of a wayfinding task. By this, six values were obtained for each segment, each reflecting its distance to one of the six navigation task destinations. The result of this first calculation is a set of values associated with each segment. Connectivity and integration reflect general spatial properties of a segment. By contrast, the ‘step depth to destination’ values are task specific measures, i.e. a segment X has different step depth to the destinations of wayfinding task 1 to 6.

The second step of analysis is to relate participants’ individual routes to the syntax properties of the building. To do this, the following measures were calculated for each behavior sequence in each navigation task:

- **Mean Connectivity in Route**: The connectivity values associated with the segments in the route were averaged.
- **Maximum Connectivity in Route**: The highest connectivity value of the segments in the route.
- **Mean / Maximum Integration in Route**: These two values are calculated in the same way as the connectivity values.
- **Mean Step Depth in Route**: The step depth of each segment to the destination is averaged. It is important, that the mean step depth of a route is calculated with the step depth values of the corresponding task destination. E.g., a route of navigation task 1 receives the average step depth of all its segments to destination of task 1. This measure reflects how far away from the destination the route is on average.
- **Maximum Step Depth in Route**: The maximum step depth of the segments in the route to the corresponding destination. This measure reflects the step depth of the segment most far away from the destination.
Please note that in the following analyses step depth plays a dual role: For the analysis of general task difficulty, we look at the step depth between the start and destination point of each of the tasks, i.e. we capture the number of turns between start and destination segment on the shortest possible, thus optimal route. In this sense step depth is a measure of the minimum behavioural and cognitive demands of a task under idealised conditions. For the analysis of the behavioural sequences actually observed, we aggregate the step depth of all segments that a participant has traversed in the course of navigating to a task destination. These capture differences in the routes chosen by the study participants and can be compared between the groups of experts and novices.

**Wayfinding Behavior**

**Task Difficulty**

In this section we reanalyze behavioural data from Hölscher et al. (2005) in the light of the spatial analyses provided in the previous sections. In table 1 we compare the performance measures with the step depth of each wayfinding task, effectively a measure of the number of turns required to get to the goal location. The general pattern of difficulty observed in the earlier study clearly corresponds with the step depth between origin and destination point of the individual tasks. This is reflected in strong correlations of step depth with the performance measures, ranging from .65 to (-).87. Overall, the pattern of difficulty of the different tasks is clearly captured with the step depth measure.

### Table 1:

<table>
<thead>
<tr>
<th>task 1</th>
<th>task 2</th>
<th>task 3</th>
<th>task 4</th>
<th>task 5</th>
<th>task 6</th>
<th>correlation with step depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>step depth</td>
<td>12</td>
<td>10</td>
<td>14</td>
<td>2</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>time [s]</td>
<td>226</td>
<td>78</td>
<td>159</td>
<td>34</td>
<td>103</td>
<td>81</td>
</tr>
<tr>
<td>stops [n]</td>
<td>2.8</td>
<td>0.4</td>
<td>1.7</td>
<td>0.3</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>getting lost [n]</td>
<td>0.7</td>
<td>0.1</td>
<td>0.5</td>
<td>0.0</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>distance [m]</td>
<td>168</td>
<td>84</td>
<td>127</td>
<td>40</td>
<td>113</td>
<td>87</td>
</tr>
<tr>
<td>way/shortest way</td>
<td>1.68</td>
<td>1.24</td>
<td>1.71</td>
<td>1.00</td>
<td>1.08</td>
<td>1.50</td>
</tr>
<tr>
<td>speed [m/s]</td>
<td>0.74</td>
<td>1.08</td>
<td>0.81</td>
<td>1.28</td>
<td>1.12</td>
<td>1.10</td>
</tr>
</tbody>
</table>

**Sequences & Expertise**

Hölscher et al. (2005) identified significant differences in the navigation behavior of experts and novices across all performance measures (Table 2). Our reanalysis intends to uncover to what degree this can be captured by space syntax based route measures.

We hypothesize that experienced and inexperienced users differ in the cognitive basis of their navigation decisions. Experienced users are likely to know the exact location of the target destination. They can plan their path from memory and do not have to rely on local or configurational features of the environment. Novices, by contrast, often do not know the position of the target exactly and rely on information made available by their surrounding. Thus we expect novices on average to more closely follow the pattern of connectivity and integration in the building, preferring to travel along path with higher values on these measures, while experts should be less susceptible to such influences. Instead, we expect experienced users to more directly travel towards the goal location, irrespective of local travel choices. This should be reflected in lower scores for the average step depth between each location in their path and the target location of each wayfinding task, since experts should choose path segments most directly connected to the goal.
The analysis of the sequence data with route-based space syntax measures is in line with these hypotheses: The mean connectivity of path segments traversed in a route by novices is significantly higher than for experienced users ($t(10) = -2.47, p = .017$; all tests one-tailed), also the maximum connectivity is significantly larger for novices ($t(10) = -2.30, p = .029$). The mean integration of path segments traversed by novices vs. experienced users shows a statistical trend in the same direction ($t(10) = -1.50, p = .082$), and the maximum integration on a route is again significantly higher for novices ($t(10) = -2.58, p = .014$). Looking at average and maximum step depth of route segments the corresponding target location of each task, the opposite pattern emerges qualitatively: While the novices more often traverse locations more distant from the target location (maximum step depth), experienced users show a least a statistical trend of avoiding such deviations throughout their path choices compared to novices (mean step depth; $t(10) = -1.57, p = .074$).

Upon closer inspection of the sequences in the building, we were able to pinpoint specific areas in the building that largely contribute to these differences. The novices more often travel through the highly connected and integrated areas in the entry-level floor, the entrance hall and the highly integrated staircase. In terms of navigation strategies, this reflects the central-point strategy, most prominent among novices and least popular among experts (see table 3). The experts, by contrast, most often knew the exact position of the goal location, which allowed for a strategy based on complete path planning, following a steeper gradient of step depth reduction. Similarly, the floor strategy was also dominantly used by those users who where highly familiar with the building. The floor strategy is characterized as first navigating vertically to the floor level of the target location as directly as possible and only then to make the horizontal approach with the target floor. With our set of tasks, the routes resulting from such a strategy are also less likely to travel via the central core of the building. Consequently, the routes used in the

<table>
<thead>
<tr>
<th>Performance</th>
<th>novice user</th>
<th>experienced user</th>
</tr>
</thead>
<tbody>
<tr>
<td>time [s] *</td>
<td>128</td>
<td>95</td>
</tr>
<tr>
<td>stops [n]</td>
<td>1.36</td>
<td>0.78</td>
</tr>
<tr>
<td>getting lost [n] *</td>
<td>0.42</td>
<td>0.17</td>
</tr>
<tr>
<td>distance [m] *</td>
<td>115</td>
<td>89</td>
</tr>
<tr>
<td>way/shortest way*</td>
<td>1.55</td>
<td>1.17</td>
</tr>
<tr>
<td>speed [m/s] *</td>
<td>0.96</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Table 2: Means and standard deviations of the performance of novices and experts and VGA measures for the corresponding path sequences, averaged across tasks. An asterisk * marks a significant difference ($p<.05$), a cross † marks a statistical trend ($p<.10$)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>novices</th>
<th>experts</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>direction strategy</td>
<td>8</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>floor strategy</td>
<td>13</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>central point strategy</td>
<td>2</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>route is well-known</td>
<td>30</td>
<td>31</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 3: Frequencies of strategy selection in novices and experts
floor strategy correspond to travel along segments of lower connectivity and integration. Thus, the different space syntax properties of the route choices of novices and experts can actually be tied to different navigation strategies.

Discussion

We have successfully connected behavioural data from a wayfinding experiment to formal spatial analysis of the setting in the previous section. In the reanalysis of the behavioural data of the experienced and inexperienced participants we could show that a newly derived set of route-based measures captures important differences between experienced and inexperienced users. These could be tied to different strategies of the wayfinders. On first sight, the differences we observed between novice and expert users are at odds with the results reported by Haq & Zimring (2003): Haq & Zimring compared the task of exploring a hospital setting with the task of navigating to concrete destinations in the building. Their participants were first time visitors. Haq and Zimring (2003) were able to show that for the exploration task, local connectivity features, but not integration, were the best predictor of trajectories observed. For the wayfinding tasks in the hospital, path choice could best be predicted by the integration values of the segments traversed, i.e. in the wayfinding task participants were more likely to travel on integrated segments. As the exploration task always preceded the wayfinding tasks, Haq & Zimring argue that participants in the wayfinding task are more experienced with the setting than the complete novices in the exploration task. Consequently, in their study integration was identified as a better predictor of expert rather than novice behavior. Our present study seems to have it the other way around: The novice users are travelling along integrated segments to a much higher degree than the experts. In fact, this apparent contradiction can be resolved quite clearly. The novice users in the hospital setting have never been in the building before, and even the relative experts observed by Haq & Zimring had actually less experience with the setting than the novices in our sample (roughly 1 hour vs. 1 day). The experts in our conference centre have yet substantially more experience (2+ weeks). Taking the results of Haq & Zimring (2003) together with our present data, we hypothesize a bell-curved relationship between experience with a setting and the value of integration as a predictor of path choice. A building user with no prior knowledge at all about the setting can logically only base his movement decisions on directly visible path choices (connectivity). As people travel in the setting for some time they experience parts of the layout and memorize at least part of their routes. Areas of high integration have inherently higher probabilities of being encountered (initially and repeatedly) during these trips and are thus more likely to be memorized and chosen for future trips. In this stage, network effects (probability of exposure) and cognitive effects (probability of memorizing & recognizing route options) work together to establish a core of main routes (cf. Hillier & lida, 2005; Kuipers et al. 2003), directly captured by high integration values. In the third and final stage, users learn more and more shortcuts to directly connect destinations and/or increasingly rely on strategies independent of how central a space is in the route graph. Consequently, high integration values correspond less clearly with the behavior of highly-experienced users compared to their intermediate counterparts.

We see our current results primarily as a starting point for further refinement, especially since the relatively small sample size may have obscured even more pronounced effects. We are currently experimenting with additional measures of route properties, taking the
sequential order of segments into account, e.g. travelling along or against a gradient of integration or connectivity.

Note that we are using space syntax as a post-hoc analytic tool in this paper. Although the study presented here is a controlled experiment, it does not include a systematic variation of space syntax properties as independent variables. For our future work it will be crucial to actively vary the space syntax properties of wayfinding tasks and layout variants in order to test the value of space syntax as a predictive theory of human spatial behavior.

Space syntax has in the past been mostly used to account for aggregate data of larger groups of people, with an emphasis on traffic flows and traffic density, often on the urban level. Wayfinding research concentrates on data from individual users with known goals and in highly controlled settings. We see great opportunity to further investigate the feasibility of connecting these two fields. It is very important for research into spatio-cognitive processes to achieve a sound description and understanding of environmental variables. The present paper – albeit clearly being a work in progress – shows some initial progress towards this long-term research goal.

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References


i. Note that the connectivity value associated with a segment is itself a mean value of the connectivity of all graph nodes in this segment.

ii. “Far away” in terms of step depth, i.e., number of edges in the graph or number of turns.

iii. The correlation with speed is negative, because only for this measure low scores indicate high performance. Note, that data was aggregated over participants for this analysis, to avoid overestimating correlations based on autocorrelations within participants across tasks. For the same reason, data for the group comparison (t-tests) was aggregated over tasks.