Perceptual Evaluation of Space in Virtual Environments

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ABSTRACT

Floor plan designs and their spatial analysis are typically constrained to blueprints and 2D projections of 3D models. Computing appropriate spatial measures from such representations provides a standard way of quantifying important aspects of the design. We wish to investigate whether a person's perceptual exploration of a space would agree with such spatial measures, that is, whether a person can roughly infer such measures by exploring a space. We perform two studies, one involving novices and the other experts. First, we conduct a perceptual study to discover whether a novice user's perception of spatial measures depends on the mode used to explore the space. Our analysis considers three spatial measures, grounded in Space-Syntax, that characterize key aspects of a design such as visibility, accessibility, and organization. We compare three modes of exploration: 2D blueprints, first-person view in a 3D simulation, and a 3D virtual reality simulation with teleportation. A correlation analysis between the users' perceptual ratings and the spatial measures, indicates that virtual reality is the most effective of the three methods, while 2D blueprints and 3D first-person exploration often fail entirely to convey the spatial measures. In the second study, experts are asked to evaluate and rank the design blueprints for each measure. The expert observations are in strong agreement with the spatial measures for accessibility and organization, but not for visibility in some cases. This indicates that even experts have difficulty understanding spatial aspects of an architecture design from 2D blueprints alone.

CCS CONCEPTS

• **Computing methodologies** → **Perception**; **Virtual reality**; **Visual analytics**; • **Human-centered computing** → **Empirical studies in visualization**; • **Applied computing** → *Computer-aided design*;

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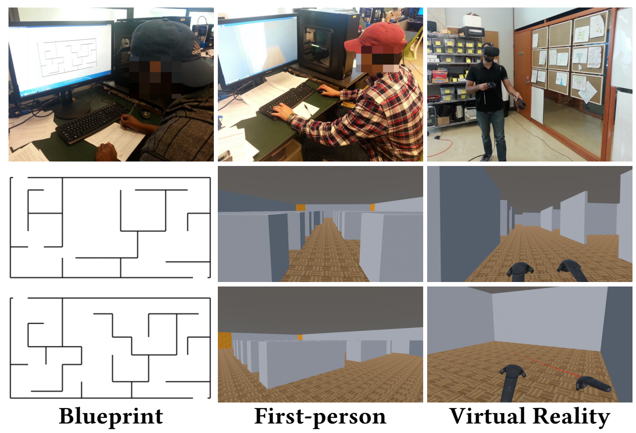

Figure 1: Design exploration modes: 2D blueprints, 3D first-person view, and virtual reality with teleportation.

KEYWORDS

Spatial analysis, navigation, perceptual study, virtual reality, architecture

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1 INTRODUCTION

Environment layouts contain complex, high dimensional information which often must be communicated to decision makers that are not expert architects. Conveying such high dimensional information using low dimensional abstractions is difficult and may lead to a loss of critical information. In general, people have a difficult time comparing spatial layouts to which they cannot relate from experience [Eliot 2002; Golledge 1997]. This is of particular interest in building design which is still primarily based on 2D projections, such as blueprints, and more recently first-person views and 3D renderings with computer game-like interfaces.

To alleviate the difficulty of interpreting high dimensional data, computational design analysis measures have been proposed and employed that analyze the effectiveness of an environment's design [Hillier and Hanson 1984; Peponis et al. 1990; Turner and Penn 1999]. These measures, or metrics, provide a computational way of understanding and comparing designs with respect to particular aspects of the environment. They also provide a means of identifying problem areas and improving the fitness of a design before a decision is made. This is particularly useful for developing automated design optimization tools. However, while these metrics can assign numerical values to environment configurations, it can be challenging for a person to understand why the environment is performing in some particular way without some context or experience with the design. It has been shown that people better understand information supplied to them in a format more in-line with their common experience [Magana 2014; Magana et al. 2012].

We investigate whether novice users can perceive spatial measures properly and whether their perception depends on the way they explore a design. We use Space-Syntax measures as the basis for our perceptual study, as they are well understood and have been extensively studied by the architectural and spatial cognition communities. An overview of Space-Syntax is given in Section 3. Our study focuses on three modes of design exploration, 2D blueprints (2D), 3D first-person walkthrough (FP), and virtual reality (VR) walkthrough. We hypothesize that VR provides an immersive experience in which spatial information is conveyed in a manner similar to a users' personal experience as they navigate through the environment.

To evaluate the effect of visual mode on spatial perception and understanding of environments, two sets of studies are performed. In the first study, novice participants are asked to rate a set of environments with respect to a set of spatial measures (Accessibility, Visibility, and Organization of space) when using different modes of display (2D, FP, and VR). For each of these measures we include one environment in two variations: one that minimizes and one that maximizes the associated spatial measure. In a nutshell, we want to see if the users will agree with the computed spatial measures on which of the two variations is better. In the second study, experts (professionals in building design and urban planning areas who are well aware of the spatial measures defined in Space-Syntax) are asked to compare the two environments using 2D blueprints, and select the environment that they believe has a better value of the spatial measure. This study explores whether the experts and the novices agree, independently of the computed spatial measures.

Our results indicate that a user's perceptual understanding of the environment is more accurate in virtual reality, and agrees with established quantitative measures of visibility, accessibility, and organization of space. We also observe that users do not agree with these measures when exploring a space using a 2D blueprint or a 3D first-person interface. The observations of the experts agree with the measures for accessibility and organization, but not for visibility in some cases. This shows that certain measures are not easy to infer from 2D blueprints alone. Lastly, the selections of the novice participants using VR agree overall with those of the experts.

2 RELATED WORK

2.1 Computational analysis of designs

Estimating the effect of a design on the people that will use it can be done primarily in two ways. First, by simulating the people in the environment using a crowd simulator and analysing performance or properties of the crowd. Second, by static analysis, typically by analysing the spatial forms of a design or their decomposition into other representations.

Crowd simulation methods model the dynamic movement of virtual agents in the environment [Kapadia et al. 2015; Pelechano et al. 2016]. A wide range of measures can be computed from the trajectories of the agents, both individual and aggregate. The most common of these measures involve utilization properties such as crowd flow, occupational density, energy expenditure, etc. These measures can then be used to inform environment design processes [Berseth et al. 2015; Cassol et al. 2017; Feng et al. 2016; Haworth et al. 2015, 2017a, 2016a,b, 2017b]. Crowd simulation based methods are more flexible than static analysis but they can be computationally expensive for large scale cases. These methods also make the assumption that the model reflects human behaviour, an assumption that has not been conclusively verified and is highly dependent on the situational context.

An alternative approach to crowd simulation is static analysis. Prior work has explored various spatial metrics that relate to human behaviour [Bafna 2003; Hillier and Hanson 1984; Jiang et al. 2000; Peponis et al. 1990; Turner and Penn 1999]. Space-Syntax is one such human-focused approach for analysing an environment. It proposes various spatial measures, based on space decompositions, to quantitatively evaluate an environment. The work in [Li and Klippel 2014] presented a methodology that uses the concept of environmental legibility in Space-Syntax to understand a person's wayfinding behaviour when navigating in complex building designs.

2.2 Perception and virtual reality in architectural design

Architectural information as spatial features are one of the key factors in planning and navigating through space. Models from architecture and urban designs are used as guidelines to improve sight, planning, and navigation in the design of virtual environments [Bridges and Charitos 1997]. A person's behaviour in two different version of the same environment can be studied using Space-Syntax measures [Kalff et al. 2012, 2010].

In [Hölscher and Dalton 2008], alternative designs of building corridors were presented to experts and non-experts as blueprint (2D) views and videos of simulated walkthroughs to investigate the visual perceptions of users. They found that the users' inputs from the videos of simulated walkthroughs have strong correlations with the ground truth environmental measures, whereas no correlation is found for blueprint views. However, there is evidence that people using head mounted displays may underestimate distance depending on measurement protocol [Grechkin et al. 2010]. Furthermore, navigation technique may play an important role in spatial understanding [Zanbaka et al. 2005].

2.3 Our work

Our work is highly motivated by an experiment to measure the perceptual judgements of experts and novice users in designs of complex corridors across different visual modes [Dalton et al. 2010]. Users were asked to complete the experiment using three different modes: by looking at blueprint views of corridor designs, videos of simulated walkthroughs, and 3D in a CAVE-based [Cruz-Neira et al. 1993] virtual reality system. However, the above studies [Dalton et al. 2010; Hölscher and Dalton 2008], are specific to wayfinding, or navigation, tasks. They do not focus on, or take into account, human-focused spatial measures such as visibility, accessibility and organization of space. They also do not compare and validate measures or ratings with respect to perception or design preferences of experts.

In this paper, a perceptual study is conducted to explore how users perceive spatial measures from Space-Syntax visibility graph analysis (degree of visibility, accessibility, and spatial organization) in environment designs when explored using different visual modes including 2D blueprints, 3D first-person view, and virtual reality. In the areas of Architecture and Spatial Cognition, these measures are considered correlated to, and therefore indicative of, human behaviour as it relates to navigation and spatial understanding [Bafna 2003]. Furthermore, unlike [Dalton et al. 2010; Hölscher and Dalton 2008], in our experimental setup participants are free to explore the presented environments for the given duration and are not bound to any wayfinding or navigation tasks. Our contributions can be summarized as follows:

- We present a framework to understand virtual spaces using human-focused spatial design measures.
- We perform two user studies (novices and experts) to identify how subjects perceive the design of a space using different modes of exploration.

3 SPATIAL ANALYSIS

Human spatial cognition and architectural attributes are the two main aspects which govern behaviour in an environment [Hölscher et al. 2005]. The effects of an environment on its users can be quantified by using measures from spatial analysis which directly relate to human behaviours. There are different dynamic [Berseth et al. 2015] and static approaches to compute these measures. A well established static approach used for spatial analysis is Space-Syntax [Bafna 2003; Hillier and Hanson 1984].

3.1 Space-Syntax

It is a framework and infrastructure to analyze the relationship between human utilization and spatial forms of environments. The fundamental principle of Space-Syntax is that use of space can be analysed by examining the environment configuration [Hillier and Hanson 1984]. In particular, environmental legibility is an important factor in way-finding in the design of an environment. Furthermore, there is evidence that aspects of 2D floor plans are strong predictors of way-finding behaviours [Weisman 1981]. Following from this assumption, numerical measures are used to evaluate the environment. These measures are based on different decompositions of space such as isovists [Benedikt 1979; Wiener et al. 2007], graphs [Hölscher and Brösamle 2007; Turner et al. 2001], and axial maps [Hillier and Hanson 1984], which make up the core of Space-Syntax analysis. Researchers have identified a promising agreement between Space-Syntax and human movement in design space [Stamps III 2002] and human perception of the environment design for cognitive measures [Haq and Zimring 2003; Hillier et al. 1993]. Space-Syntax has also been used to investigate customer behaviour by identifying their path typologies and patterns in a supermarket [Gil et al. 2009].

To investigate this significant connection, we consider computing graph-based spatial measures from Space-Syntax which are believed to directly relate to human behaviours [Bafna 2003; Hillier and Hanson 1984]. An environment configuration can be analysed via Space-Syntax by decomposing its space into a *visibility graph* [Desyllas and Duxbury 2001; Turner and Penn 1999]. The *visibility graph* V_V with edges E_V is then processed by computing measures of features related to the spatial layout of the environment. These measures are tree depth, degree, and entropy which relate to accessibility, visibility, and organization of space respectively. These measures make up a significant part of Space-Syntax and are well-known in the architecture and urban planning communities. However, they have not been investigated sufficiently in the applications of computer graphics and applied perception (e.g. VR and human perception). The spatial measures used in this work are defined as follows:

3.1.1 Accessibility (Tree Depth). Consider the forest F_i that consists of all trees whose root is $v_i \in V_V$. The Tree Depth d_i is the rank of the graph tree T_i which has the minimum depth in F_i. It is defined as: $\boldsymbol{d_i = \mathrm{rank}(T_i)}$. Accessibility is measured as negative tree depth. A node with low accessibility, or high tree depth, is connected to other regions of the visibility graph through a longer sequence of nodes. Intuitively, this measures the difficulty of navigating from a particular standpoint, and is related to how many turn decisions are required to move from one point to another. This approximately captures how people move within a space.

3.1.2 Visibility (Degree). The degree of visibility k_i of vertex v_i is the number of neighbours N_i incident to the vertex $v_i \in V_V$ connected by edges $E_i \subset E_V$. The degree of visibility is defined as: $\boldsymbol{k_i = |N_i|}$. Regions with high visibility provide a better field of view and are considered more connected with the surrounding space. For example, if a user wants to install safety signs, then positioning them in high visibility regions might be preferred. Visibility can also be thought of as the feeling of "openness" from a particular standpoint in space.

3.1.3 Organization (Entropy). The entropy h_i at vertex v_i is predicted on a probability distribution $p_i(d)$ of a tree T_i with n_i^d vertices at each level d. The entropy (organization) can then be computed as: $\boldsymbol{h_i = -\sum_{d=0}^{height(T_i)} p_i(d)\log_2 p_i(d)}$. Entropy measures the organization of an environment, or how easy it is for an individual to plan and navigate through the space. If a node has low entropy then the steps required to reach other regions in the environment from that node is unbalanced, in the sense that the number of options along the path varies widely. Intuitively, the less organized a space is the easier it is to get lost or confused when navigating.

These measures can be computed over an entire environment or specific regions of interest and are often visualized using heat maps overlaid on top of 2D layouts. For the purposes of comparatively evaluating designs of environments, the average value of the measure is considered.

These spatial measures are widely used in the architectural design community. In this work, we are using these measures to run a perceptual study. To provide a deeper interpretation and comparative evaluation of these measures (i.e. computed values – numbers), a separate study is needed.

4 STUDY 1 - PERCEPTUAL EVALUATION OF SPATIAL MEASURES AND MODES OF VISUAL EXPLORATION

Spatial measures provide architects and designers with fast computational means of analysing an environment design. However, displaying or showcasing a design to a novice user has traditionally been done using blueprints, models, and more recently digital first-person views (typically using computer game or rendering engines). We hypothesize that virtual reality (using state-of-the-art head-mounted displays), over these more traditional viewing modes, affords novice users with the ability to best perceive the spatial layout of an environment in terms of accessibility, visibility, and organization of space.

4.1 Material and Methods

4.1.1 Measures. Three spatial measures (accessibility, visibility, and organization of space) from Space-Syntax analysis are used in this experiment. All three have their own unique interpretations to quantify the performance of architectural environments with respect to human occupancy and behaviour (see Section 3).

4.1.2 Environments. A variety of real-scaled environments including an art gallery, a grocery store, and an office (maze) are used to illustrate the effect of spatial measures from Space-Syntax analysis, as shown in Figure 2. Each environment is chosen to exemplify a particular spatial measure. That is, the art gallery is tuned for 'Accessibility', the grocery store is tuned for 'Visibility', and the office (maze) is tuned for 'Organization' of the space. All three environments have been tuned to produce two design variations (design conditions) representing extremes, low average value (MIN) and high average value (MAX), of their respective spatial measure.

We utilize these measures to investigate how well novice users (Section 4) and experts (Section 5) perceive and differentiate environments. Figure 2 shows the three environments with two design variations. The two left columns (a and b) show the MAX condition with high average values of their associated spatial measure, while the two right columns (c and d) show the MIN condition with low average values. Each pair of columns shows the layout of the environments with and without the associated spatial measure displayed as an overlaid heatmap. The art gallery (top row) is associated with accessibility, the grocery store (middle row) with visibility, and the maze (bottom row) with organization of space. Table 1 shows the pre-computed values of the spatial measures for each environment variation. Since the MIN/MAX design variations of each environment are tuned for a specific spatial measure

Environment	Accessibility	Visibility	Organization
Art Gallery-min	**3.758**	395.926	1.4655
Art Gallery-max	**3.8037**	392.5512	1.4326
Grocery Store-min	3.0133	**141.56**	1.1192
Grocery Store-max	3.054	**149.3974**	1.1335
Maze-min	5.6132	98.3605	**2.1219**
Maze-max	6.9855	74.4237	**2.5361**

Table 1: Pre-computed spatial measures from Space-Syntax analysis. The art gallery, grocery store, and maze, each has two design conditions (MIN/MAX) for extreme values of accessibility, visibility, and organization of the space.

it is possible that they will have conflicting MIN/MAX values for metrics that they are not tuned for.

4.1.3 Apparatus. Each part of the experiment is completed using a particular visual mode including a 2D blueprint, interactive 3D first-person walkthrough, and a virtual reality (VR) system with teleportation. The 2D blueprints are skeletal views of the designs of the environments. Each blueprint displays wall and scale information to the participant. The participant viewed the blueprints on a high resolution (1080p) widescreen (16:9) computer monitor. The 3D first-person walkthroughs are interactive 3D models with basic ambient lighting (no shadow) built in the Unity3D game engine. The participants were given a mouse (look direction) and keyboard (translation) to control a virtual camera. The participant viewed the environments on a high resolution (1080p) widescreen (16:9) computer monitor.

In this experiment, the latest consumer level VR system is used, the HTC Vive. This system affords room-scale interaction and navigation using two hand-held controllers. The participants view the world using a head mounted display (HMD) OLED screen affording 1080x1200 pixel resolution per eye at a 90Hz refresh rate and a latency of 22ms.

4.1.4 Participants. 18 people (4 female and 14 male between 22 and 35 years of age) voluntarily participated in the experiment. They were paid 10 dollars per hour. The participants were mostly university students studying in computer science, digital media, or closely related fields. In order to recruit novices for this experiment, only those participants who reported no prior understanding of architectural and Space-Syntax concepts were selected.

4.1.5 Experiment procedure and task. The experiment is delivered in three portions. In each portion, each participant was provided with two different design variations (MIN/MAX) to explore. Each participant was then asked to perceptually rate the environment for the three spatial measures (accessibility, visibility, and organization of space), based on their understanding, by assigning a rating value on a ten-point Likert scale (1 – 10) with 1 being 'very low' and 10 being 'very high'. Every participant was given 20 minutes for each visual mode to complete the tasks. To prevent any sort of learning effect between participants, the experimental conditions are delivered with balanced latin-square design for the selection of visual modes and environments. Before the start of the experiment, each participant was briefly informed about the spatial measures

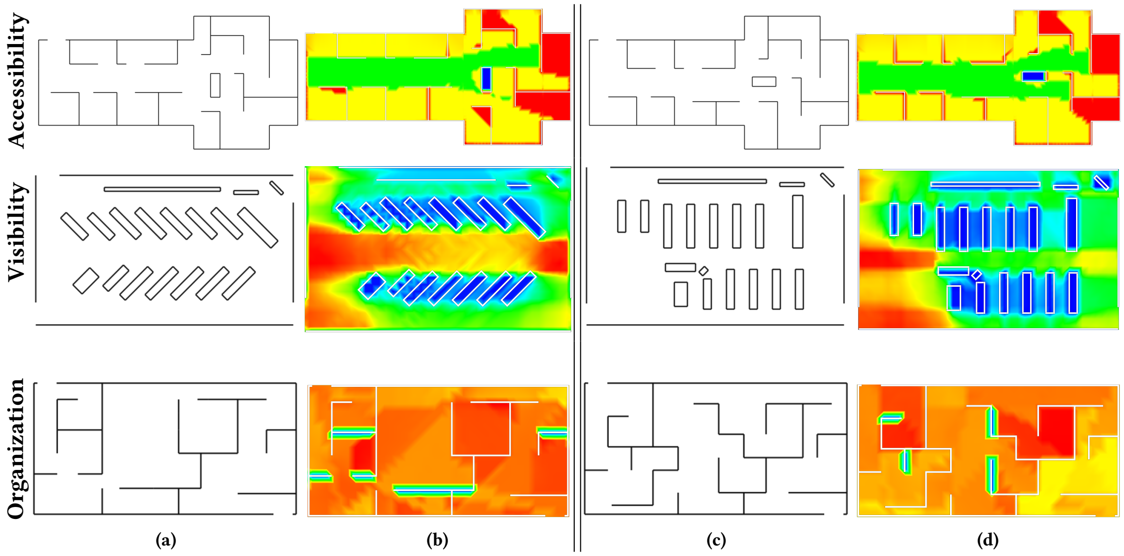

Figure 2: The three test environments and their two design variations with the associated spatial measure shown as an overlaid heat map (red area in the environments show the high values and blue show the low values of the spatial measure). Columns (a) and (b) correspond to the design variation with high average value (MAX) while (c) and (d) to the design variation with low value (MIN) of a spatial measure. TOP – Art Gallery associated with accessibility. MIDDLE – Grocery store associated with visibility. BOTTOM – Office (maze) associated with organization of the space.

from Space-Syntax analysis along with the examples on a sample environment. The training material is provided as a supplementary document.

It has been reported in the literature that working with VR may cause VR-induced sicknesses like eye strain, dizziness, nausea, and some other symptoms similar to motion sickness [Nichols and Patel 2002]. To minimize motion sickness, the teleportation exploration/navigation method is utilized. This method allows a user to jump to a new position in the environment from which they can explore locally. Furthermore, each participant's interpupillary distance (IPD) is measured, and the headset lenses are adjusted accordingly.

4.2 Analysis

4.2.1 Independent variables. Pre-computed spatial measures from Space-Syntax analysis for each design variation of each environment were the primary independent variables (also referred to as computed spatial measures or ground truth). As well, the apparatus for each visual mode is considered an independent variable.

4.2.2 Dependent variables. A number of values were captured during each part of the experiment on a ten-point Likert scale (1 – 10) for these three spatial measures: (1) Accessibility, (2) Visibility, and (3) Organization of the space.

To understand the relationship between participants' ratings and the pre-computed spatial measures of the environments, a Pearson product-moment correlation analysis is performed (see Figure 3). More specifically, there is a focus on the correlations for the spatial measure every environment is tuned for.

A three-way repeated measures analysis of variance was conducted on the influence of independent variables (visual modes, spatial measures, design variations of environments) on the users' perceptual ratings. Visual modes included three levels (Blueprint, First-person, Virtual Reality), spatial measures included three levels (Accessibility, Visibility, Organization) and design variations of environments consisted of two levels (MIN, MAX).

A one-way between subjects analysis of variance was performed to statistically compare the ratings of novice participants among all three visual modes.

4.3 Results

On average, participants spend 9 *minutes* in blueprint, 12 *minutes* in first-person and 10 *minutes* in VR mode of exploration.

4.3.1 Mean of users' ratings. Figure 4 shows the mean values of the participants' rating over both MIN/MAX design variations of the environments in all three visual modes. The vertical bars show the standard deviation.

4.3.2 Correlation analysis between users' ratings and pre-computed spatial measures. *Art gallery:* The users' ratings positively correlated with accessibility in virtual reality ($r = +.38$, $p = .03$), but were not significantly correlated in first-person ($r = +.05$, $p = .86$) and 2D blueprint ($r = +.11$, $p = .76$) modes at confidence interval $\alpha = 0.05$. *Grocery store:* The users' ratings were not significantly correlated with visibility in first-person ($r = -.20$, $p = .63$) and 2D blueprint ($r = -.05$, $p = .88$) modes, but significantly correlated in virtual reality ($r = +.47$, $p = .01$) mode at confidence interval $\alpha = 0.05$. *Office (maze):* The users' ratings significantly correlated with pre-computed organization values in 2D blueprint ($r = -.39$, $p = .03$) and virtual reality ($r = +.63$, $p = .04$) modes, but not

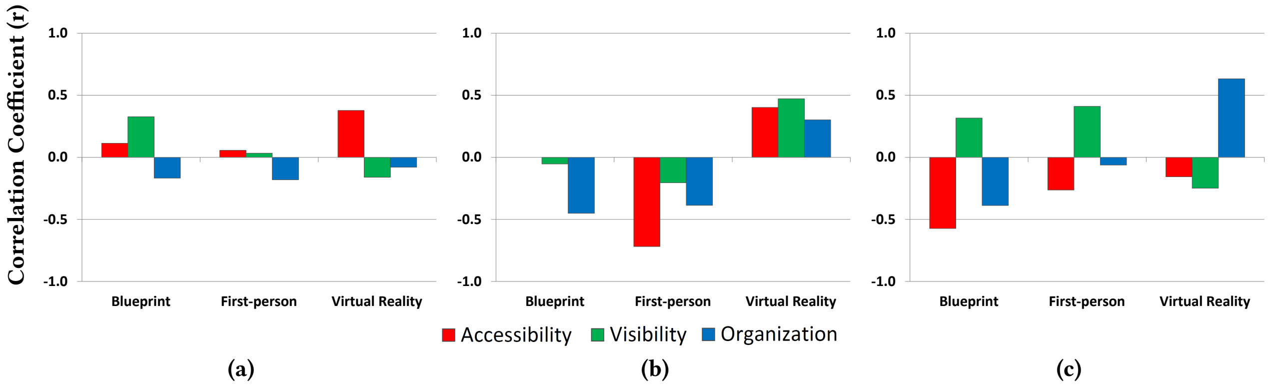

Figure 3: Linear correlation between participants' perceptual ratings and spatial measures from Space-Syntax. (a) Art Gallery, (b) Grocery Store, (c) Office. VR shows a moderate positive correlation for the spatial measure every environment is tuned for.

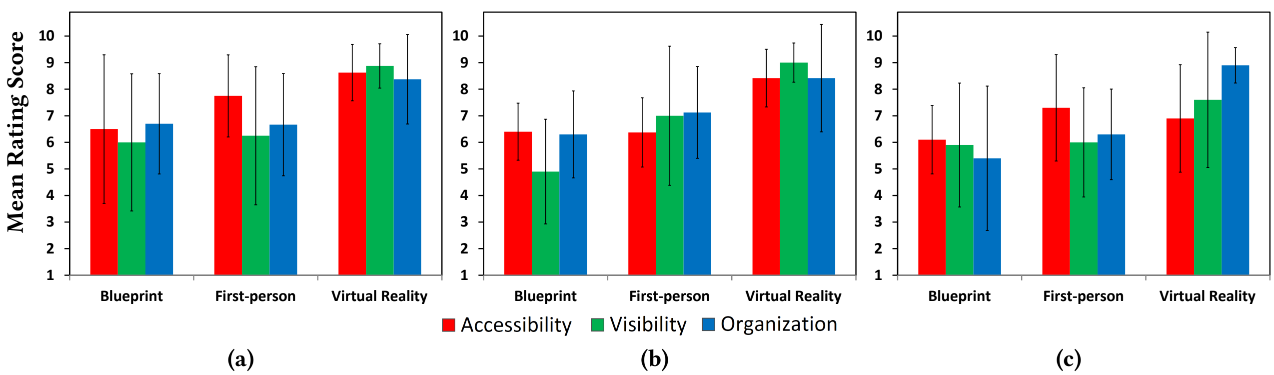

Figure 4: Mean ratings from participants over both MIN/MAX design variations. Vertical bars show standard deviation (SD). (a) Art Gallery, (b) Grocery Store, and (c) Office. The VR mode has less SD and a higher mean than the other two visual modes.

significantly correlated in first-person ($r = -.06$, $p = .86$) mode at confidence interval $\alpha = 0.05$.

4.3.3 Comparison of users' ratings across all visual modes. There was a significant effect of visual modes on participants' rating at a significance level of $p < 0.05$ for the three conditions [F(2, 87) = 17.92 = 3.0341e−07], see Figure 5. A post-hoc comparison was then performed using the Tukey HSD test to compare across conditions. The test indicates that virtual reality mode has higher effects than 2D blueprint and first-person modes.

4.3.4 Influence of independent variables on users' ratings. A three-way repeated measures analysis of variance was conducted on the influence of independent variables on the users' perceptual ratings:

Art gallery: All effects were statistically significant at the 0.05 significance level. The main effect for visual modes yielded an F ratio of [F(2, 28) = 14.29, p = 0.000] indicating a significant difference among Blueprint, First-person and VR modes. The main effect for spatial measures yielded an F ratio of [F(2, 28) = 7.51, p = 0.002] indicating a significant difference among Accessibility, Visibility and Organization measures. The main effect for design variations of environments yielded an F ratio of [F(1, 14) = 20.17, p = 0.001] indicating a significant difference between MIN and MAX variations. The interaction effects *visual modes * design variations* (F(2, 28) = 14.45, p = 0.000) and *visual modes * spatial measures * design variations* (F(4, 56) = 3.680, p = 0.010) were significant, whereas the interaction effects *visual modes * spatial measures* (F(4, 56) = 2.177, p = 0.083) and *spatial measures * design variations* (F(2, 28) = 1.320, p = 0.283) were not significant.

Grocery store: Only a single effect (visual modes factor) was statistically significant at the 0.05 significance level. The main effect for visual modes yielded an F ratio of [F(2, 28) = 69.75, p = 0.000] indicating a significant difference among Blueprint, First-person and VR modes. The main effect for spatial measures and design variations of environments yielded an F ratio of [F(2, 28) = 0.69, p = 0.510] and [F(1, 14) = 0.50, p = 0.489] respectively, indicating no significant difference among Accessibility, Visibility and Organization measures and between MIN and MAX design variations. The interaction effects *visual modes * spatial measures* (F(4, 56) = 6.89, p = 0.000) and *visual modes * design variations* (F(2, 28) = 4.24, p = 0.025) were significant, whereas the interaction effects *spatial measures * design variations* (F(2, 28) = 0.20, p = 0.813) and *visual modes * spatial measures * design variations* (F(4, 56) = 0.72, p = 0.577) were not significant.

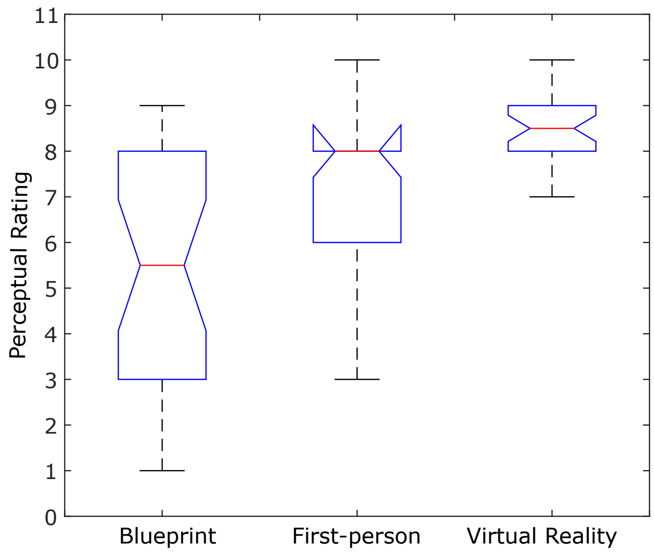

Figure 5: One-way analysis of variance (ANOVA) of perceptual ratings to analyze the differences among visual modes. The test indicates that virtual reality mode is significantly different from the other two. It has significantly higher perceptual ratings than blueprint and first-person. Bars show minimum and maximum rating values.

Office (maze): All effects were statistically significant at the 0.05 significance level except for the design variations factor. The main effect for visual modes and spatial measures yielded an F ratio of [F(2, 28) = 11.70, p = 0.00] and [F(2, 28) = 14.23, p = 0.000] respectively, indicating a significant difference among Blueprint, First-person and VR modes, and among Accessibility, Visibility and Organization measures. The main effect for design variations of environments yielded an F ratio of [F(1, 14) = 2.42, p = 0.142] indicating no significant difference between MIN and MAX design variations. The interaction effects *visual modes * spatial measures* (F(4, 56) = 6.345, p = 0.000) and *visual modes * design variations* (F(2, 28) = 3.47, p = 0.045) were significant, whereas the interaction effects *spatial measures * design variations* (F(2, 28) = 0.89, p = 0.419) and *visual modes * spatial measures * design variations* (F(4, 56) = 1.43, p = 0.235) were not significant.

4.4 Discussion

The summary statistics indicate that participants had better understanding of the spatial measures when exploring the environments using virtual reality over other visual modes. On the other hand, standard deviation values are much smaller for all three environments when using virtual reality. Furthermore, first-person performed better than 2D blueprint. Overall, accessibility and organization were more highly rated spatial measures than visibility in all three visual modes.

Correlation analysis reveals several interesting insights. In particular, the benefits of using VR to understand the spatial features of an environment seem to be consistent in all three experiment cases. *Art Gallery:* The correlation coefficients show that the participants perceived the accessibility of the space most accurately in the virtual reality mode, and least accurately using the first-person mode. It is also interesting to note that for all three visual modes the correlation between users' ratings and pre-computed accessibility values is positive, unlike the other two measures. *Grocery Store:* The correlation coefficients show a negative relation between the participants' ratings and pre-computed visibility values for both first-person and 2D blueprint modes. In contrast, the virtual reality mode has a moderate to low positive correlation. *Office (maze):* The moderate positive correlation with virtual reality, as opposed to the low and weak negative correlations of blueprint and first-person, indicates that participants were able to perceive the organization of the space in agreement with its pre-computed values only using this mode.

Results from three-way (*visual modes X spatial measures X design variations of environments*) repeated measures analysis of variance show that the main effect as well as interaction effect involving visual modes factor has great influence on the users' ratings and has significant difference among blueprint, first-person and virtual reality modes. Figure 6 shows the estimated marginal means of users' perceptual ratings on the three visual modes.

The one-way analysis of variance shows that participants' perception and understanding of the spatial measures from one of the modes is greatly different from the other two, and therefore, rejects the null hypothesis [Jr. and Jr. 1995]. These results suggest that virtual reality does have an effect on a person's perception and understanding of space. More specifically, the results suggest that when someone uses virtual reality as a mode to explore environments, the person's perception is more accurate with respect to spatial measures from Space-Syntax analysis.

5 STUDY 2 - EXPERTS' PERCEPTION OF SPATIAL MEASURES

Blueprints are a common means of conveying both draft and final configurations in architectural designs. It is expected that experts are capable of inferring a large amount of information from blueprints. It remains to be seen how well the computed spatial measures conform to an expert's spatial intuition. The agreement between the two sources of spatial perception is key to validating the usefulness of spatial measures for the amount of design-time information they provide.

5.1 Material and Methods

5.1.1 Environments. The blueprints of the three environments from Section 4.1, an art gallery, a grocery store, and an office (maze), are used in this experiment, see Figure 2.

5.1.2 Apparatus. The 2D blueprints are skeletal views of the environment designs. Each blueprint displays wall and scale information to the participant. The participants viewed the blueprints using their own computer monitors via an online survey with high resolution images.

5.1.3 Participants. 14 experts (6 female, 7 male and 1 non-binary/third-gender) voluntarily participated in the experiment. Table 2 shows the demographic information of the participants.

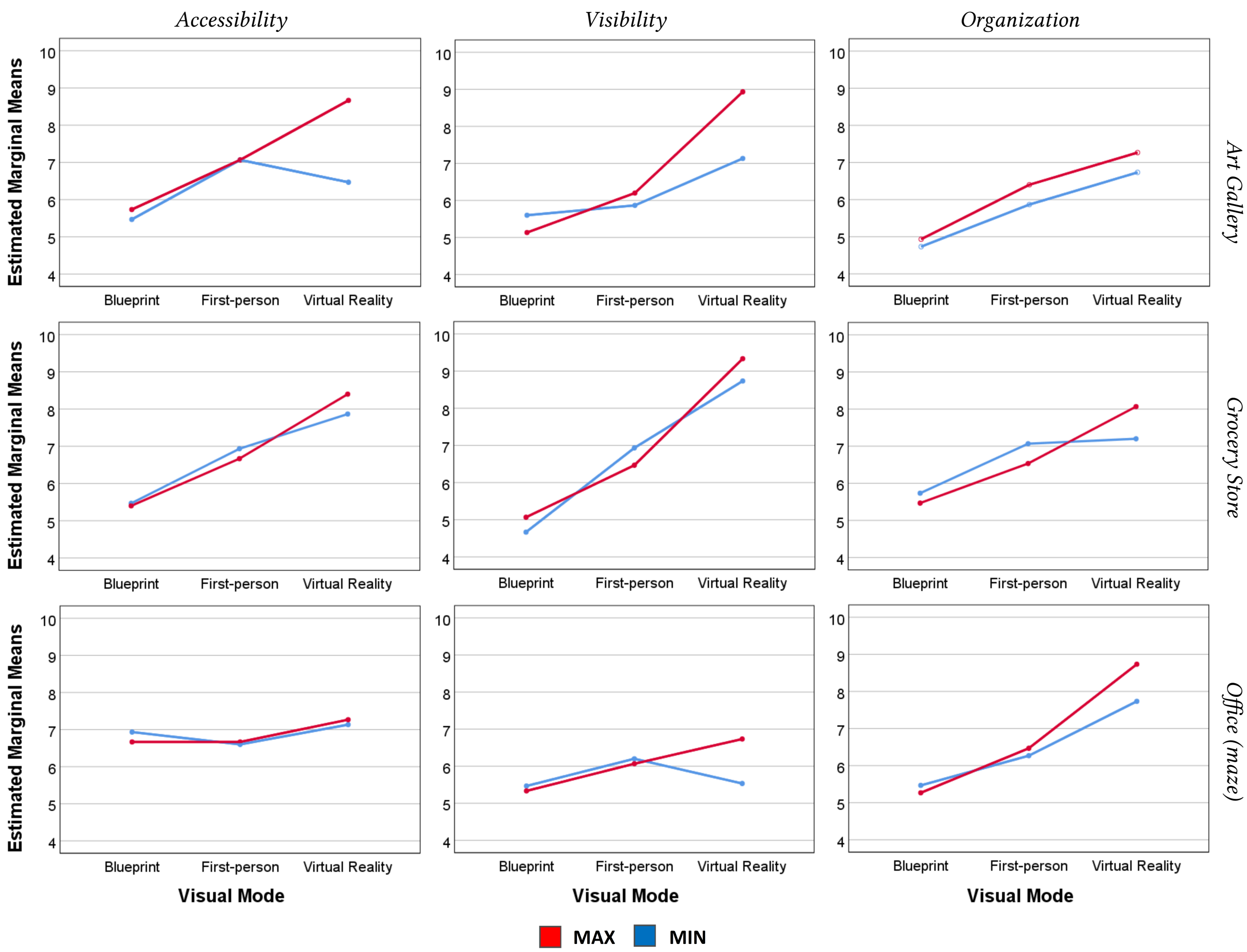

Figure 6: Estimated marginal means of users' perceptual ratings on the three visual modes. Virtual Reality shows the highest influence on user perception.

In order to recruit experts for this experiment, all participants self-evaluated their knowledge and skills in the area of architectural designs, urban planning, and Space-Syntax spatial measures on a five-point Likert scale-based assessment. On average, participants rated 4 and greater on a scale of 1–5 regarding their prior experience. Furthermore, participants were asked to rate their understanding of Space-Syntax spatial measures, for which the average recorded response was 3.43 on a scale of 1–5. This shows that the participants had above-average prior understanding of Space-Syntax spatial measures. To further increase this understanding, they were briefly informed about the Space-Syntax spatial measures along with examples. Table 2 shows the recorded domain knowledge responses from the participants.

5.1.4 Experiment procedure and task. This experiment is conducted as an online survey. Both MIN and MAX variations of the environments are presented randomized side-by-side as blueprints with scaling information. Each participant makes a binary selection to identify the design variation they believe has highest value (MAX) for each Space-Syntax spatial measure.

5.2 Analysis

5.2.1 Independent variables. The design variations of the environments (MIN/MAX) were the primary independent variables. The pre-computed spatial measures (Visibility, Accessibility and Organization) for each design variation and environments were also independent variables.

5.2.2 Dependent variables. The experts selected design variation of each environment and for each spatial measure is captured by the survey.

5.3 Results

Figure 7 summarizes the results from experts' selections. The blue portion of the bars shows the percentage of experts who correctly

Demographic Information

Gender	Sex	Age	Country of Residence
Female: 6 (42.9%)	Female: 6 (42.9%)	25 - 34 years old: 10 (71.4%)	Canada: 9 (64.3%)
Male: 7 (50%)	Male: 7 (50%)	35 - 44 years old: 4 (28.6%)	United Kingdom: 1 (7.1%)
Non-binary/Third-gender: 1 (7.1%)	Intersex: 1 (7.1%)		Pakistan: 4 (28.6%)

Domain Knowledge

	Poor	Below Average	Average	Above Average	Excellent	AVG. scale 1–5
Ability to interpret architectural or interior designs?	0 (0%)	0 (0%)	1 (7.1%)	7 (50%)	6 (42.9%)	4.36
Prior experience with architecture or interior designs?	0 (0%)	1 (7.1%)	3 (21.4%)	5 (35.7%)	5 (35.7%)	4.00
Prior experience in urban planning and design?	0 (0%)	1 (7.1%)	1 (7.1%)	4 (28.6%)	8 (57.1%)	4.36
Prior understanding of spatial Space-Syntax measures?	1 (7.1%)	1 (7.1%)	3 (21.4%)	9 (64.3%)	0 (0%)	3.43

Table 2: Demographic information and domain knowledge ratings of expert participants (self-provided).

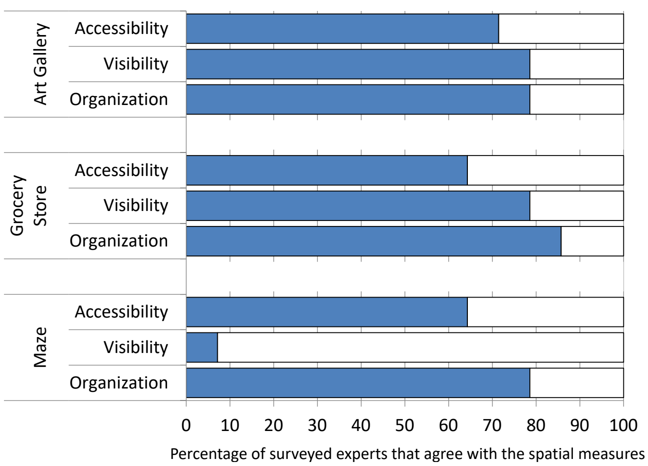

Figure 7: The blue portion of the bars shows the correctness of experts’ identification of design variation agrees with the pre-computed spatial measures.

identified the design variations of the environments that agreed with the pre-computed Space-Syntax spatial measures (Table 1). That is, the portion of experts which correctly identified the design variations which have the highest value (MAX) of visibility, accessibility, and organization. On average, 68% of the experts correctly identified the design variations.

5.4 Discussion

The results show that the majority of experts perceived the Space-Syntax spatial measures as intended and correctly differentiated between the two design variations (MIN/MAX). More specifically, the majority of the experts agreed with the pre-computed spatial measures in the cases of the art gallery and the grocery store. For the office (maze) environment, the majority correctly identified the accessibility and organization but did not agree with visibility of the space. It is therefore fair to conclude that even for experts is not easy to evaluate certain spatial characteristics of an environment from blueprints alone.

6 CONCLUSION

In this paper, we have conducted a perceptual study to find out whether a novice user’s perceptual understanding of an environment agrees with established spatial measures such as those defined by Space-Syntax analysis, and whether that agreement depends on the mode of visual exploration. Experimental results indicate that using virtual reality to explore a space results in better agreement between the users’ perception of the space and the computed spatial measures. In most cases, virtual reality is the only mode that shows a significant positive correlation between the two. These results have implications for how the sharing and collaboration of environment design can be done most effectively. It appears that novices may gain a significantly better understanding of a potential design if they are allowed to experience it using VR. Intuitively, this means personal experience with a design is useful in communicating attributes of the space. Though virtual reality is not reality, it provides an ad-hoc, yet immersive, means of approximating a person’s experience without the need to be physically in the space. The results from three-way *(visual modes X spatial measures X design variations of environments)* analysis of variance show significant differences among the three visual modes for the main effect as well as the interation effects involving visual modes factor. Furthermore, the estimated marginal means show that virtual reality is the most effective of the three visual modes.

We have also performed a second study where experts with prior knowledge of spatial measures and with proficiency in architectural designs were asked to identify design variations of the environments. The expert observations are mostly in agreement with the computational MIN/MAX measures (Table1) for accessibility and organization, but not entirely for visibility, indicating that even experts may have difficulty interpreting spatial measures from blueprints alone. Our results indicate that virtual reality may be the best method for analysing three-dimensional spaces for architectural design applications. These results motivate further investigation in to the perception, evaluation, and communication of designs involving complex spatial forms.

The presented analyses do have limitations. There are other measures related to how a person would perceive the environment such as light or soundscape that can be explored. As well, Space-Syntax, as noted in section 3, encompasses many more measures derived from more spatial decompositions. This study focuses on graph-based decompositions, namely the visibility graph, and measures related directly to human use and perception of an environment. Furthermore, expert perceptual evaluations could be explored further. In future work, the analysis of experts' experience across the different modes would facilitate this discussion. A separate study needs to be done for deeper interpretation and comparative evaluation of the spatial measures (i.e. computed values – numbers). Lastly, the work does not test how different navigation modes might affect visual perception of the environment. For example, blueprints have no navigation method to compare other modes to. In this study, best navigation method available was used for each visual mode.

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REFERENCES

Sonit Bafna. 2003. Space Syntax: A Brief Introduction to Its Logic and Analytical Techniques. *Environment and Behavior* 35, 1 (2003), 17–29.
Michael L Benedikt. 1979. To take hold of space: isovists and isovist fields. *Environment and Planning B: Planning and design* 6, 1 (1979), 47–65.
Glen Berseth, Muhammad Usman, Brandon Haworth, Mubbasir Kapadia, and Petros Faloutsos. 2015. Environment optimization for crowd evacuation. *Computer Animation and Virtual Worlds* 26, 3–4 (2015), 377–386.
Alan Bridges and Dimitrios Charitos. 1997. *The Architectural Design of Virtual Environments.* Springer Netherlands, Dordrecht, 719–732.
Vincius J Cassol, Estêvão Smania Testa, Cláudio Rosito Jung, Muhammad Usman, Petros Faloutsos, Glen Berseth, Mubbasir Kapadia, Norman I Badler, and Soraia Raupp Musse. 2017. Evaluating and Optimizing Evacuation Plans for Crowd Egress. *IEEE Computer Graphics and Applications* 37, 4 (2017), 60–71.
Carolina Cruz-Neira, Daniel J. Sandin, and Thomas A. DeFanti. 1993. Surround-screen Projection-based Virtual Reality: The Design and Implementation of the CAVE. In *Computer Graphics and Interactive Techniques (SIGGRAPH '93).* ACM, New York, NY, USA, 135–142.
Ruth Dalton, Christoph Hoelscher, T. Peck, and V. Pawar. 2010. Judgments of building complexity & navigability in virtual reality. In *Spatial Cognition 2010.* 49–64.
Jake Desyllas and Elspeth Duxbury. 2001. Axial Maps and Visibility Graph Analysis: A comparison of their methodology and use in models of urban pedestrian movement. In *Space Syntax Symposium.* 27.1–27.13.
John Eliot. 2002. About spatial intelligence: I. *Perceptual and motor skills* 94, 2 (2002), 479–486.
Tian Feng, Lap-Fai Yu, Sai-Kit Yeung, KangKang Yin, and Kun Zhou. 2016. Crowd-driven Mid-scale Layout Design. *TOG* 35, 4 (2016), 132:1–132:14.
Jorge Gil, Eime Tobari, Maia Lemlij, Anna Rose, and AR Penn. 2009. The differentiating behaviour of shoppers: clustering of individual movement traces in a supermarket. (2009).
Reginald G Golledge. 1997. *Spatial behavior: A geographic perspective.* Guilford Press.
Timofey Y Grechkin, Tien Dat Nguyen, Jodie M Plumert, James F Cremer, and Joseph K Kearney. 2010. How does presentation method and measurement protocol affect distance estimation in real and virtual environments? *ACM TAP* 7, 4 (2010), 26.
Saif Haq and Craig Zimring. 2003. Just down the road a piece the development of topological knowledge of building layouts. *Environment and behavior* 35, 1 (2003), 132–160.
Brandon Haworth, Muhammad Usman, Glen Berseth, Mubbasir Kapadia, and Petros Faloutsos. 2015. Evaluating and Optimizing Level of Service for Crowd Evacuations. In *Motion in Games.* ACM, 91–96.
Brandon Haworth, Muhammad Usman, Glen Berseth, Mubbasir Kapadia, and Petros Faloutsos. 2017a. On density–flow relationships during crowd evacuation. *Computer Animation and Virtual Worlds* 28, 3-4 (2017).
Brandon Haworth, Muhammad Usman, Glen Berseth, Mahyar Khayatkhoei, Mubbasir Kapadia, and Petros Faloutsos. 2016a. Towards Computer Assisted Crowd Aware Architectural Design. In *SIGCHI Extended Abstracts.* ACM, 2119–2125.
Brandon Haworth, Muhammad Usman, Glen Berseth, Mahyar Khayatkhoei, Mubbasir Kapadia, and Petros Faloutsos. 2016b. Using Synthetic Crowds to Inform Building Pillar Placements. In *Workshop on VHCIE, Virtual Reality.* IEEE, 7–11.
Brandon Haworth, Muhammad Usman, Glen Berseth, Mahyar Khayatkhoei, Mubbasir Kapadia, and Petros Faloutsos. 2017b. CODE: Crowd-optimized design of environments. *Computer Animation and Virtual Worlds* (2017).
Bill Hillier and Julienne Hanson. 1984. The social logic of space, 1984. *Cambridge: Press syndicate of the University of Cambridge* (1984).
Bill Hillier, Alan Penn, Julienne Hanson, Tadeusz Grajewski, and Jianming Xu. 1993. Natural movement: or, configuration and attraction in urban pedestrian movement. *Environment and Planning B: planning and design* 20, 1 (1993), 29–66.
Christoph Hölscher and Martin Brösamle. 2007. Capturing indoor wayfinding strategies and differences in spatial knowledge with space syntax. In *Space Syntax Symposium.*
Christoph Hölscher and Ruth Conroy Dalton. 2008. *Comprehension of Layout Complexity: Effects of Architectural Expertise and Mode of Presentation.* Springer Netherlands, Dordrecht, 159–178.
Christoph Hölscher, Tobias Meilinger, Georg Vrachliotis, Martin Brösamle, and Markus Knauff. 2005. Finding the Way Inside: Linking Architectural Design Analysis and Cognitive Processes. In *Spatial Cognition: Reasoning, Action, Interaction (SC'04).* Springer-Verlag, 1–23.
Bin Jiang, Christophe Claramunt, and Björn Klarqvist. 2000. Integration of space syntax into GIS for modelling urban spaces. *Applied Earth Observation and Geoinformation* 2, 3 (2000), 161–171.
Nancy A. Obuchowski Jr. and Howard E. Rockette Jr. 1995. Hypothesis testing of diagnostic accuracy for multiple readers and multiple tests an anova approach with dependent observations. *Communications in Statistics - Simulation and Computation* 24, 2 (1995), 285–308.
Christopher Kalff, David Keuhner, Martin Senk, Ruth Dalton, Gerhard Strube, and Christoph Hoelscher. 2012. Turning the Shelves: Empirical Findings and Space Syntax Analyses of Two Virtual Supermarket Variations Judgements of Building Complexity and Navigability in Virtual Reality. In *Space Syntax Symposium*, Margarita Greene, José Reyes, and Andrea Castro (Eds.). PUC, Santiago de Chile, 1–23.
Christopher Kalff, David Kühner, Martin Senk, Ruth Dalton, and Christoph Hoelscher. 2010. Turning the shelves: empirical findings and space syntax analyses of two virtual supermarket variations. In *Spatial Cognition 2010.* Springer Verlag, 25–48.
Mubbasir Kapadia, Nuria Pelechano, Jan Allbeck, and Norm Badler. 2015. Virtual Crowds: Steps Toward Behavioral Realism. *Synthesis Lectures on Visual Computing* 7, 4 (2015), 1–270.
Rui Li and Alexander Klippel. 2014. Wayfinding Behaviors in Complex Buildings: The Impact of Environmental Legibility and Familiarity. *Environment and Behavior* 48, 3 (2014), 482–510.
Alejandra J Magana. 2014. Learning strategies and multimedia techniques for scaffolding size and scale cognition. *Computers & Education* 72 (2014), 367–377.
Alejandra J Magana, Sean P Brophy, and Lynn A Bryan. 2012. An integrated knowledge framework to characterize and scaffold size and scale cognition (FS2C). *Science Education* 34, 14 (2012), 2181–2203.
Sarah Nichols and Harshada Patel. 2002. Health and safety implications of virtual reality: a review of empirical evidence. *Applied Ergonomics* 33, 3 (2002), 251 – 271. Fundamental Reviews in Applied Ergonomics 2002.
Nuria Pelechano, Jan M Allbeck, Mubbasir Kapadia, and Norman I Badler. 2016. *Simulating Heterogeneous Crowds with Interactive Behaviors.* CRC Press.
John Peponis, Craig Zimring, and Yoon Kyung Choi. 1990. Finding the building in wayfinding. *Environment and behavior* 22, 5 (1990), 555–590.
Arthur E Stamps III. 2002. Entropy, visual diversity, and preference. *The Journal of general psychology* 129, 3 (2002), 300–320.
Alasdair Turner, Maria Doxa, David O'sullivan, and Alan Penn. 2001. From isovists to visibility graphs: a methodology for the analysis of architectural space. *Environment and Planning B: Planning and design* 28, 1 (2001), 103–121.
Alasdair Turner and Alan Penn. 1999. Making isovists syntactic: isovist integration analysis. In *Symposium on Space Syntax.* Citeseer, 103–121.
Jerry Weisman. 1981. Evaluating architectural legibility way-finding in the built environment. *Environment and behavior* 13, 2 (1981), 189–204.
Jan M Wiener, Gerald Franz, Nicole Rossmanith, Andreas Reichelt, Hanspeter A Mallot, and Heinrich H Bülthoff. 2007. Isovist analysis captures properties of space relevant for locomotion and experience. *Perception* 36, 7 (2007), 1066–1083.
Catherine A Zanbaka, Benjamin C Lok, Sabarish V Babu, Amy Catherine Ulinski, and Larry F Hodges. 2005. Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment. *IEEE TVCG* 11, 6 (2005), 694–705.