The Influence of Global and Local Spatial Configuration on Wayfinding

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Knowledge about the configuration of an environment is used preferentially when navigating through an urban environment (Penn, 2003). However, it the locus of this effect is poorly understood. One possibility is that the local environment, such as the shape of an intersection, is sufficient to determine route choice in the context of the global configuration of an environment (Meilinger, Franz, & Bülthoff, in press; Meilinger, Knauff & Bülthoff, 2008). Two experiments were performed to investigate this hypothesis using two novel virtual environments, one with a simplistic configuration, and one with a more complicated configuration. In Experiment 1, peripheral vision was either available or constrained throughout a wayfinding task. A significant influence of global configuration information with minimal use of local configuration account was found. In Experiment 2, central vision was either limited to the local intersection or unconstrained. Again, a strong effect of configuration was found, with limited evidence for the use of local visual information. The results support a synergistic mechanism of wayfinding where the environmental configuration is used to inform existing knowledge about the environment.

Acknowledgements

I would like to give special thanks to my advisor, Colin Ellard, for his guidance, encouragement, and enthusiasm for my research.

I would also like to thank Daniel Smilek and Britt Anderson for their insightful comments on the design and presentation of this research.

In addition, I would like to thank the members of the Research Lab for Immersive Virtual Environments for their assistance throughout the course of this study. In particular, I would like to thank Deltcho Valtchanov for his technical assistance during the design of the experiments.

Dedication

This thesis is dedicated to my wife and family, without their support I would not have come this far.

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1.1 Introduction

Public transit maps typically provide relational information about an environment rather than an accurately scaled representation of an environment. However, when we enter the environment, we are able to use this relational information effectively despite perceiving the environment in its true form. How are we able to use relational information when navigating? A field known as space syntax appears to suggest that this is possible because we use relational information in the wayfinding process (Penn, 2003).

1.1.1 Space Syntax

Space syntax is a field that assumes that the function of the layout of a built environment is achieved purely through measures of structural configuration (Hillier, 1996; Hillier & Hanson, 1984). The designer of an urban space creates a space to serve a specific function, such as to encourage or discourage traffic through particular areas. Space syntax assumes that a person navigating through an urban environment implicitly understands this syntax and therefore wayfind accordingly. Space syntax accounts for this assumption by decomposing an environment into a set of topological descriptions. This topological composition contrasts with a method that requires referencing to the Euclidean properties of the environment. The result is a description of an environment which describes its configuration in a consistent and systematic way.

In decomposing an environment into a set of topological descriptions, space syntax converts the paths in an environment into a series of lines representing potential lines-of-sight from every possible location within the environment. Each line, known as an axial line, must be straight and connect with at least one other position in the environment. The resulting map, consisting all of the axial lines, will therefore be sensitive to the overall configuration of each space within the environment. A large intersection allows for a greater number of axial lines connecting to adjacent spaces, while a smaller intersection limits the number of axial lines that can be created. Figure 1 demonstrates how a typical Euclidean map (Panel A) can be portrayed as an axial map (Panel B). Abstractly, the axial map provides a description of how well an environment supports unobstructed viewpoints. As no reference is made to discrete distance between points in the construction of the axial map, the resulting map is considered a topological or relational representation of the space.

To quantify the axial map a series of calculations can be performed. While space syntax involves a number of different techniques three will be discussed in the context of this paper:

Connectivity. Connectivity accounts for the number of axial lines that a specific axial line bisects. A higher connectivity value represents a path or line-of-sight which intersects a larger number of lines than a lower connectivity value. As portrayed in Panel C of Figure 1, lines which allow more unobstructed lines-of-sight, extending through more than one intersection of the environment, are more likely to be associated with a high connectivity value. Abstractly, a high connectivity value for a specific line represents a position in the environment that would allow a person located anywhere along the line to see other open areas located nearby. It is therefore a measure of whether an individual path or line-of-sight within the environment will lead to perceiving more or less visual information relative to the current position of the navigator.

Integration. Integration accounts for how well an axial line is connected to the environment as a whole. Panel D of Figure 1 demonstrates typical integration values found in an environment. Integration is calculated as the average number of direction changes necessary to reach every other axial line in the environment from a specific axial line. As lower number of turns is preferred, the average is then reported as the mathematical reciprocal. A position which is represented by a higher integration value will require fewer turns to get to another position within the environment, reflecting a relatively simple spatial configuration around that location. As a result, it can be considered an analogue of how difficult an environment is to navigate. It is possible to limit the distance to which the integration value is calculated such that the average is computed for only those lines within the distance, rather than for all lines within the environment. Limiting the distance reduces the influence of the outer boundaries of the environment on the integration value. Integration calculated for all lines to a radius of three turns, rather than without limiting turns, is considered to most accurately predict human movement (Conroy, 2001; Hillier, 1996).

Intelligibility. Intelligibility is considered to be a representation of how navigable is an environment. It is calculated as the correlation between connectivity, a measure of how well a location affords perceiving information about the environment, and integration, a measure of how simple it is to navigate to the next location. A high correlation would reflect an environment where well-connected paths also are contained in areas which require fewer turns, and poorly connected paths are not, described as high intelligibility. In contrast, a low intelligibility would reflect an environment in which the connectedness of the paths is largely independent from the spatial complexity of the surrounding environment, reflecting a more complicated environment, described as low intelligibility.

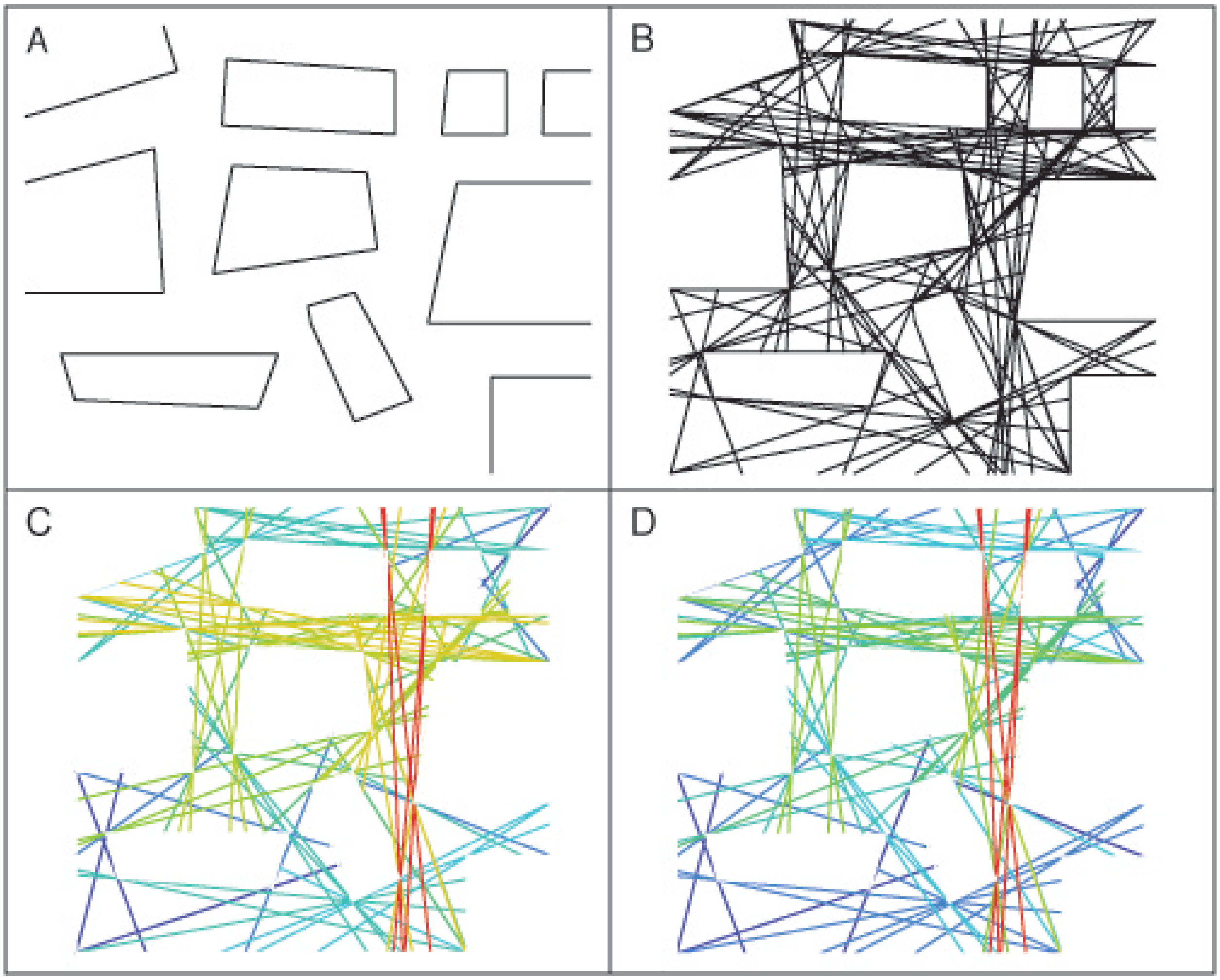


Figure 1. Decomposition of a traditional map into measures used by space syntax: original map (A), all-line axial map (B), connectivity, where red is high and blue is low (C), and integration, where red is high and blue is low (D).

1.1.2 Global Spatial Configuration

The use of relationally-based space syntax to investigate human movement behaviour has shown an interesting pattern of results. A growing number of studies suggest that the intelligibility of an environment can have a significant influence on how easily the environment is learned (Haq, 1999a; Peponis et al, 1990; Hillier, 1987), and can be used to predict both pedestrian (Hillier, Penn, Hanson, Grajewski & Xu, 1993; Peponis, Hadjinikolaou, Livieratos, & Fatouros, 1989; Hillier, Burdett, Peponis, & Penn, 1987) and vehicular (Penn, Hillier, Banister, & Xu,1998a, 1998b) movement through an environment at an aggregate level. A space or specific entrance to an environment which is more integrated and connected within an environment will experience more traffic (Haq, 1999a) than those with low values. It has also been demonstrated that spaces with high intelligibility will be used more efficiently, with travel through an intelligible environment being shorter, quicker, and associated with pausing at meaningful locations, than that observed in a low intelligibility environment (Conroy, 2001). Collectively, these studies appear to suggest that not only does the configuration of an environment influence wayfinding, but that the decisions we make while navigating through an environment are sensitive to relationships between each location rather than relying purely on what is perceived from a specific location.

Further support for the use of relational measures has been found in the mental representation of an environment, known as a cognitive map. A cognitive map can be determined by asking a navigator to draw the layout of an environment from memory (Lynch, 1960). A number of similarities were found between axial maps and cognitive maps.

First, Euclidean distance between elements tends to be distorted by the degree to which a person experiences those features (Lee, 1970). Locations which are rarely explored by the navigator have a tendency to be drawn further away than those that are encountered more often by the navigator. Additionally, paths which are more integrated within the environment are more likely to be included in a cognitive map (Kim & Penn, 2004). The concordance between cognitive maps and axial maps appears to suggest that not only do we use relational measures in wayfinding, but that this may occur as a result of cognitive maps being constructed similarly to axial maps.

The correspondence between relational syntax measures and both the mental representation and use of an environment suggests that relationships between features of an environment may influence wayfinding more than some visually-based factors. Most notably, a review of the predictive power of space syntax concluded that between sixty and eighty percent of all human movement can be accounted for by the syntax of a space alone (Penn, 2003). Penn went on to argue that relational metrics underlying configuration are recruited beyond those of local environmental features (i.e., landmarks, attractors, etc.) and individual goals and motivations. However, before accepting this conclusion, it is necessary to determine how we are able to perceive the relational structure of an environment.

The structure of a space could be perceived in one of two ways. It is possible that the configuration of an environment could be perceived in the way that local intersections encountered along a route are arranged. An alternative possibility is that it is necessary to perceive more than the local space in order to deduce the configuration of an environment and make decisions accordingly.

1.1.3 Local Spatial Configuration

One potential explanation of the predictive power of relationally-based space syntax is that the configuration of an environment influences the uniqueness of certain local features of an environment, such as its intersections, and the way they afford the perception of distant spaces. Several investigations have examined the effect of the shape of intersections on both wayfinding behaviour and memory for routes and features in an urban environment (Meilinger, Franz, & Bülthoff, in press; Meilinger, Knauff & Bülthoff, 2008). These investigations examined the size of a viewing area (isovist: Benedikt, 1979) as influenced by the shape of an intersection. The authors found that when a participant learned a route, performance was significantly worse on a memory task, and more wayfinding errors were made at T-shaped intersections than at non-T shaped intersections (Meilinger, Franz, & Bülthoff, in press). Further investigation suggested that this effect was most influenced by a verbal processing (Meilinger, Knauff & Bülthoff, 2008) rather than a visual or spatial processing account. Together, these studies provide support for the importance of local configuration of an environment as an influence on the wayfinding process irrespective of the relationship between the distant configuration observable from a location, which would portray relational information about the environment. However, as the global configuration of the environment was not manipulated in these studies it is difficult to determine whether local or global factors are being used in the wayfinding process.

In contrast, the influence of intersections on the wayfinding process has been investigated in a study which compared varying levels of intelligibility on the wayfinding process (Conroy, 2001). Participants were asked to make their way to a landmark somewhere within one of seven environments and then make their way back to the start position.

Participants demonstrated a preference to maintain straight paths (Conroy-Dalton, 2003; Conroy, 2001). However, more interestingly, participants tended to pause more often in intersections located in the high intelligibility environments (Conroy, 2001), a configuration more conducive to intersections which afford perception of more visual information.

Taken together, these studies provide some support for the influence of the local environment, especially that of the configuration of intersections, on the wayfinding process. When an intersection is small or shaped in a specific way, performance on wayfinding tasks becomes significantly poorer. This appears to suggest some initial tangibility for the hypothesis that the effect of space syntax is a result of local configuration of space rather than one of an understanding of global configuration of an environment.

1.1.4 The Current Study

The current study further investigated the influence of local configuration, as embodied by intersections, on the use of global relational measures. In order to examine this question, two novel virtual environments were used: one high intelligibility environment, and one low intelligibility environment. Participants completed a wayfinding task consistent with the method used by Conroy (2001), which had participants navigate from a start position to a landmark located within the environment and then return to the start position once the landmark had been found. The influence of local configuration was investigated in two experiments. In the first experiment, the size of the viewing area was manipulated by limiting perceptual information to ascertain whether the use of global relational information is influenced by the limited fields-of-view in smaller intersections (Meilinger, et al., in press; Conroy, 2001). In a second experiment, the extent to which the local configuration of the environment is able to afford relational information was examined against the use of global structural knowledge. Both experiments compared the distance moved, task completion time, number of pauses, and range of gaze during pauses to assess the effect of the manipulations on the wayfinding process. Gender was also examined, as it has not been previously investigated in the context of global relational cues. While traditionally women have shown poorer performance than men on tasks requiring spatial orientation (Prestopnik & Roskos-Ewoldsen, 2000), subsequent investigation has suggested that differential performance between the genders is only found when field-of-view is limited (Tan, Czerwinski, & Robertson, 2006). Accordingly, it is expected that women will perform worse than men only when visual information is limited.

1.2 Experiment 1

The purpose of Experiment 1 was to evaluate whether the effect of intersections on the wayfinding process is a function of decreased visual information being afforded by the shape of the intersection. The influence of local configuration was assessed by having participants navigate with either a naturalistic field-of-view, or constrained field-of-view where central vision was only available. Equal numbers of men and women were asked to participate so that gender effects could be assessed. Participants were asked to navigate through either a high intelligibility or a low intelligibility environment to a landmark and then return to the starting position.

1.2.1 Method

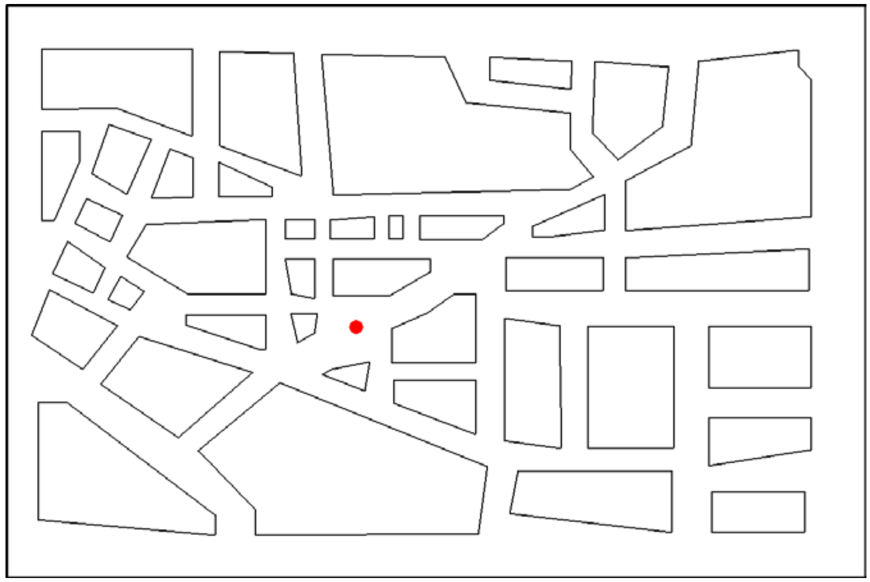
Participants. Ninety-six undergraduate students attending the University of Waterloo participated in the experiment in exchange for course credit. The average age of the sample was 20.71 (SD=1.85). Equal numbers of male and female participants were recruited, with an average age of 21.14 (SD=2.23) for males, and 20.28 (SD=1.46) for females. All participants were fluent English speakers, and had normal or corrected-to-normal vision. Participants who were prone to motion sickness or had a vestibulocochlear disorder were excluded from participation.

Visual Displays. Participants were tested using a script written within Vizard, a Python-based virtual reality toolbox (Worldviz Inc.). The rendered environment was presented to the participant using one of two head-mounted display (HMD) units, one with a constrained field-of-view (FOV), the nVisor SX (nVIS), and one with a naturalistic field-of-view, the Wide5 (Fakespace). The nVisor SX HMD, constructed by nVIS, has a 44 degree horizontal/35 degree vertical field-of-view (FOV). It operates at 24-bit color depth with a video resolution of 1280x1024 pixels and a 60 Hz image refresh rate. The HMD weighs approximately 1 kilogram. The Wide5 HMD, constructed by Fakespace Labs, has a 150 degree horizontal/90 degree vertical field-of-view. It operates at 24-bit color depth with a video resolution of 1600x1200 pixels and a 60 Hz image refresh rate. The HMD weighs approximately 1 kilogram.

Virtual Environments. Two novel environments were created using Sketch-up 6.0 (Google Inc.), a 3D modeling and graphic design package. The models were constructed to be 1200m x 800m. Within these environments, 38 buildings were created and arranged, with each building being constructed to the same height of 8 meters, but in a variety of shapes and sizes. The environments can be seen in Figure 2. A high intelligibility environment was designed, with the majority of well-connected paths being directly connected to each other. A low intelligibility environment was then designed based on the first environment, but adjusted the layout such that the connected paths were not connected directly with each other. This manipulation resulted in an intelligibility value of 0.958 for the high intelligible environment and 0.8258 for the low intelligibility environment. A square was placed at the relative center of both environments. The paths between buildings were marked with a uniform cobblestone texture, and the buildings were given a small brick texture with uniformly arranged windows. The outer boundary of the environment consisted of an 8m tall wall which was easily identifiable by a large dark red brick texture.

A landmark, as can be seen in Figure 3, was constructed to resemble a spire, measuring 3m x 3m and standing to a height of 8m. The landmark was placed in the

A



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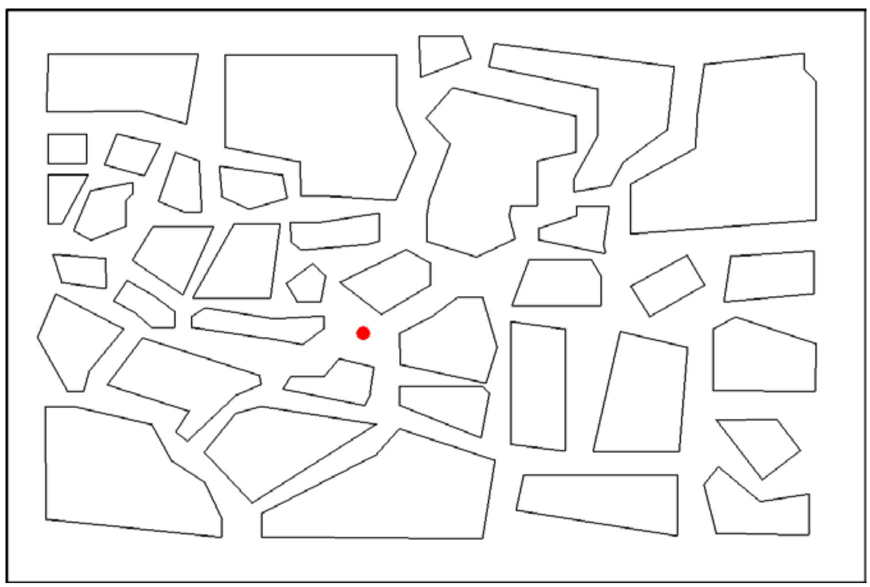

Figure 2. The virtual environments used in Experiment 1 and Experiment 2: the high intelligibility environment (A) and the low intelligibility environment (B). The dot in each environment represents the location of the target landmark.

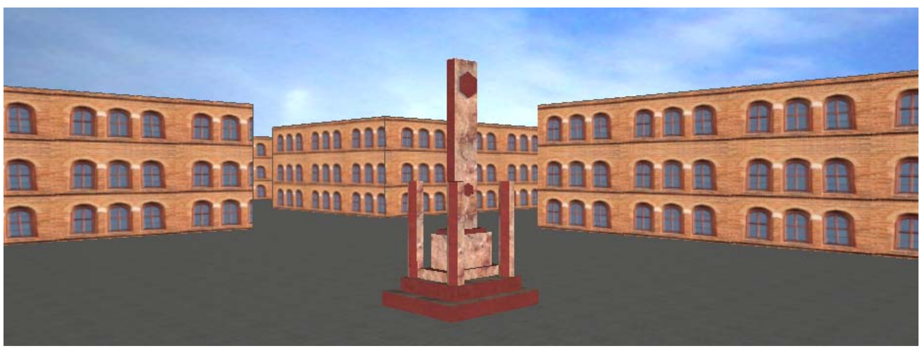

Figure 3. A view of the landmark and surrounding buildings within the virtual environment.

environment at two locations: one within the central square, and one located directly adjacent to the start position.

Movement Control. Participants navigated through the virtual environment by using a wireless mouse and head position tracking. Depressing the left mouse button resulted in forward movement which ceased when the button was released. Direction changes were made by having the participant turn their head to the desired direction. This resulted in both the visual image and their heading within the environment re-orienting to the appropriate direction. Participant position within the environment and heading were recorded at an interval of 15 milliseconds.

Procedure. Participants were initially greeted by an experimenter and briefed on the equipment to be used within the experiment. All participants then read and signed an informed consent letter. Each participant was then randomly assigned to one of four conditions (high/low intelligibility, nVIS/Wide5), while maintaining equal gender within each condition.

The HMD was placed on the participant by an experimenter and adjusted by the participant until it was comfortable and provided a clear image. The participant was then immersed within a virtual environment. Each participant started next to a monument, located in the northwest corner of the environment. The participant was informed that they were starting near a monument, and that an identical version of the monument was located somewhere within the city located around them. The participant was instructed to find the second monument and informed that upon locating the second monument they would be required to return to the start position as marked by the first monument. The participant was given as much time as they required to complete the task.

The participant was required to remain standing throughout the experiment to ensure that external cues or restricted body movement did not influence their navigation within the virtual environment. An experimenter monitored the participant throughout the experiment for task completion and early signs of simulator sickness.

Following completion of the experiment, the participant was debriefed and encouraged to ask questions about their experience and the experiment.

Data Analysis. All measures were extracted from each participant's data file. Total distance traveled, total time, and velocity were extracted directly from the data file. The participant's pause behaviour was calculated as any drop in velocity below the average velocity for each participant. This method was used to scale the pause measure to a meaningful pause length for each participant. While the participant was considered to be pausing, the change in head direction (gaze range) was recorded. The average gaze range was then calculated for the participant. The participant's route was quantified using Levenshtein distance analysis (Levenshtein, 1965). A string was constructed for each participant's path using the method presented in Figure 4. Levenshtein distance analysis calculates the number of insertions, deletions, and substitutions necessary to make two strings identical. The average Levenshtein distance between each participant's string and those of other participant's within each experimental group was calculated using this data. The average distance represents a measure of how atypical a string was compared to others, with a higher number representing a more dissimilar string.

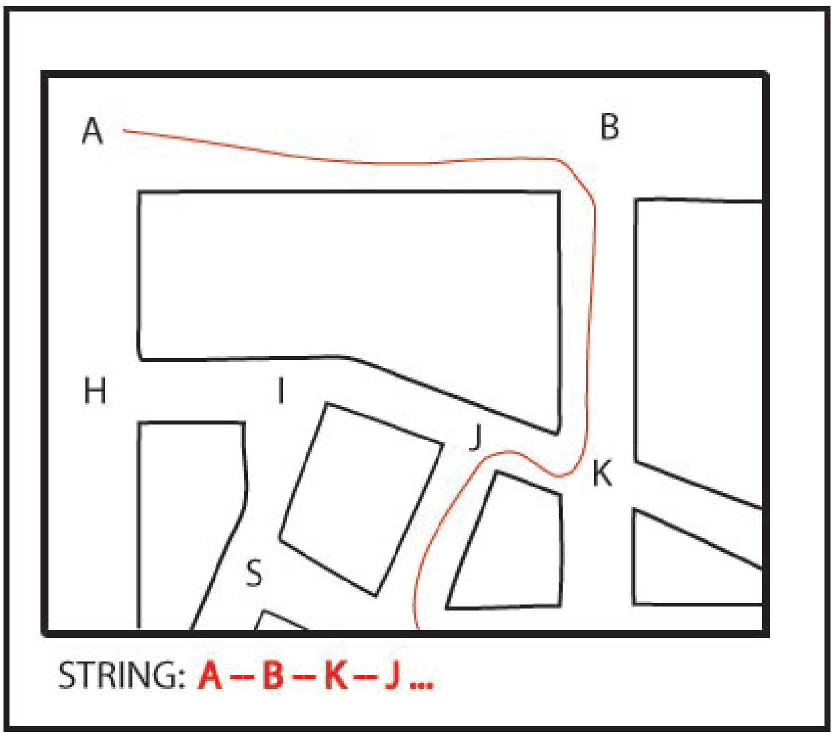

Figure 4. Path strings were constructed for each participant. As the participant encountered a new intersection the character representing the intersection was recorded.

1.2.2 Results

The results will be presented in two sections. In the first section movement variables were analyzed to determine the influence of intelligibility and field-of-view on movement behaviour, as it has been investigated most thoroughly in a space syntax account of human movement. In the second section the degree to which pause and gaze behaviour was influenced by each factor was assessed to determine whether local configuration or global configuration influence decision times. Multivariate ANOVAs were performed on both sections, with significant effects being supplemented by simple effects testing.

Movement Behaviour. The overall movement paths for all participants are presented for the high and low intelligibility environments in Figure 5. A 2 (High Intelligibility/Low Intelligibility) x 2 (150 degree FOV/60 degree FOV) x 2 (Male/Female) multivariate ANOVA was performed on the total distance, total time, and path similarity factors.

The influence of Intelligibility on each of the movement behaviour variables can be seen in Table 1. A main effect of Intelligibility, $F(1, 92) = 66.035$, $MSE = 419.664$, $p<0.001$, $\eta^2 = 0.429$, was found such that participants traveled further in the low intelligibility environment than in the high intelligibility environment. This pattern was also found in a main effect of Intelligibility on the total movement time measure, $F(1, 92) = 85.132$, $MSE = 3601.704$, $p<0.001$, $\eta^2 = 0.492$. Participants navigated through the high intelligibility environment more directly than in the low intelligibility environment. A main effect of Intelligibility on path similarity was also found, $F(1, 92) = 487.190$, $MSE = 4551.260$, $p<0.001$, $\eta^2 = 0.847$. Participant paths were more similar in the high intelligibility environment than in the low intelligibility environment. These results support the effect of intelligibility on wayfinding established by

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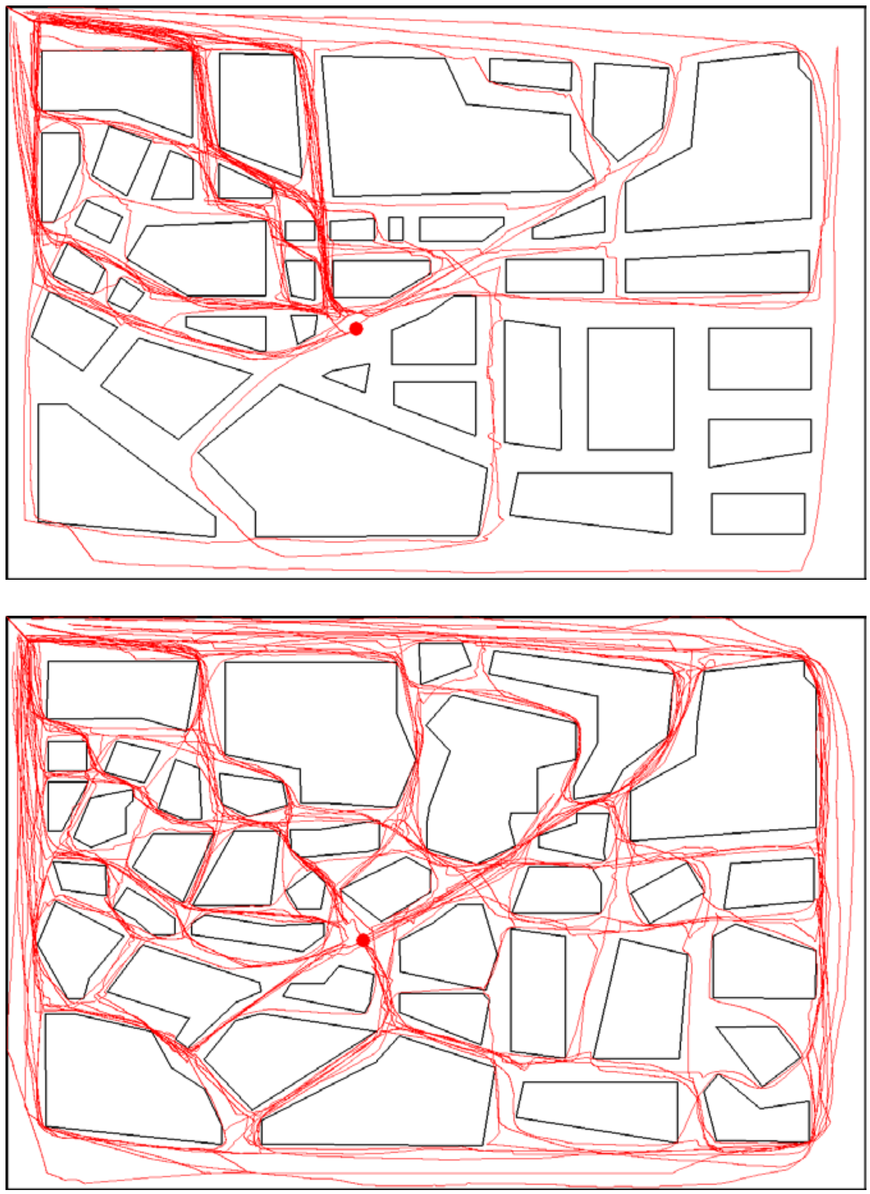

Figure 5. Movement paths for participants in Experiment 1 for the high intelligibility (A) and low intelligibility (B) environments.

Table 1. Movement Behaviour measures by intelligibility.

	Spatial Intelligibility		
	Low Intelligibility	*High Intelligibility*	*P-Value*
Total Distance (kms)	8.1695 (0.4658)	3.9879 (0.1867)	P<0.001
Total Time (s)	23.3986 (1.2371)	11.1483 (0.5347)	P<0.001
Path Similarity (Levenshtein distance)	24.77 (0.56)	11.00 (0.41)	P<0.001

Standard error of means are shown in parentheses.

previous investigations where navigation is performed more efficiently in high intelligibility environments than in low intelligibility environments.

A main effect of Field-of-View was found on path similarity, $F(1, 92) = 7.682$, $MSE = 71.760$, $p<0.001$, $\eta^2 = 0.080$. Participant's overall paths were more similar to each other when field-of-view was constrained (Levenshtein distance=17.02, SE=1.13) than when it was more

naturalistic (Levenshtein distance=18.75, SE=1.09). However, an effect of Field-of-View was not found for total distance or total time, and no significant interactions were observed between Field-of-View and Intelligibility. While paths did show a tendency to be more similar to each other as a function of field-of-view, the failure to find an influence of field-of-view on either movement time or distance made confirming a hypothesis based on the decrease in visual information as the locus for intelligibility effects difficult.

No significant main effects of Gender were found on any of the movement behaviour measures, and Gender was not found to interact significantly with Field-of-View. However, a significant interaction between Gender and Intelligibility was found for total time, $F(1, 92) = 5.119$, $MSE = 216.550$, $p<0.026$, $\eta^2 = 0.055$. Simple effects analysis on the time data, shown in Figure 6A, revealed that women took longer than men to complete the task in the high intelligibility environment, but no such difference was observed in the low intelligibility environment. Distance was found to follow the same pattern of results, Figure 6B, but did not achieve significance ($p<0.117$). Additionally, a significant interaction between Gender and Intelligibility was observed on path similarity, $F(1, 92) = 14.747$, $MSE = 137.760$, $p<0.001$, $\eta^2 = 0.144$. The path similarity for men and women is presented in Figure 6C. Simple effects analysis showed that the paths for both men and women were found to be significantly less

A

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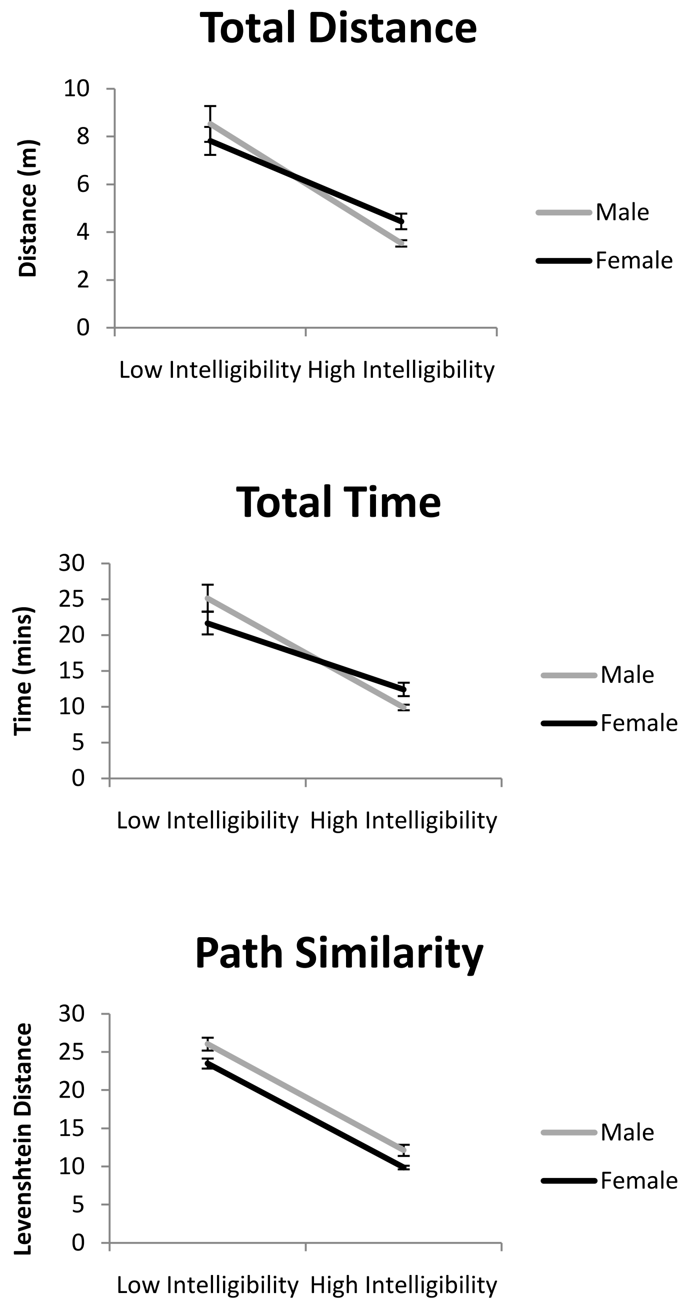


Figure 6. Total path distance, total task time, and path similarity for men and women immersed in high and low intelligibility environments with standard error.

similar in the low intelligibility environment when compared against the high intelligibility environment. Further, the paths engaged in by men were significantly more dissimilar from each other than those of women. Taken as a whole this pattern of results suggests that global relational cues are used differently by men and women, with men utilizing the structure of the environment in a slightly more efficient and consistent way than women.

No interactions between Intelligibility, FOV, and Gender were observed.

Pause Behaviour. The total number of pauses, average time spent pausing, and gaze range while pausing were examined using a 2 (High Intelligibility/Low Intelligibility) x 2 (150 degree FOV/60 degree FOV) x 2 (Male/Female) multivariate ANOVA.

The results for Intelligibility on the pause behaviour factors are presented in Table 2. A main effect of Intelligibility was found for the total number of pauses, $F(1, 92) = 17.748$, $MSE = 446.344$, $p<0.001$, $\eta^2 = 0.168$. Participants paused more frequently in the low intelligibility environment than in the high intelligibility environment. Likewise, a main effect of Intelligibility on average pause time, $F(1, 92) = 4.776$, $MSE = 11.036$, $p<0.032$, $\eta^2 = 0.051$, was found. Participants paused for longer periods of time in the low intelligibility environment than in the high intelligibility environment. A main effect of gaze range while pausing was found, $F(1, 92) = 8.371$, $MSE = 25187.760$, $p<0.005$, $\eta^2 = 0.087$, but did not follow the same pattern of results as the pause frequency and pause time measures. Participants gazed over a small area on average in the low intelligibility environment than the high intelligibility environment. Overall, this pattern of results suggests a decrease in examining the environment throughout the wayfinding process in low intelligibility environments.

Table 2. Cognitive demand measures by intelligibility.

	Spatial Intelligibility		
	Low Intelligibility	*High Intelligibility*	*P-Value*
Pause Frequency	11.38 (0.72)	7.06 (0.75)	P<0.001
Average Pause Time (s)	3.95 (0.31)	3.27 (0.18)	P<0.032
Gaze Range	115.63 (6.99)	148.02 (9.23)	P<0.005

Standard error of means are shown in parentheses.

A main effect of Field-of-View was found on average pause time, $F(1, 92) = 23.725$, $MSE = 54.828$, $p<0.001$, $\eta^2 = 0.212$, was found with longer pause times (4.36s, SE=2.19) being observed in participants with constrained field-of-view than for those with the naturalistic field-of-view (2.86s, SE=0.80). The Field-of-View manipulation did not have an effect on frequency of pauses or gaze range while pausing. Intelligibility and Field-of-View were not found to interact significantly on any of the gaze behaviour variables.

A main effect of Gender was found on frequency of pausing, $F(1, 92) = 4.394$, $MSE = 110.510$, $p<0.039$, $\eta^2 = 0.048$, average pause time, $F(1, 92) = 7.397$, $MSE = 17.094$, $p<0.008$, $\eta^2 = 0.078$, and gaze range while pausing, $F(1, 92) = 5.505$, $MSE = 16563.760$, $p<0.021$, $\eta^2 = 0.059$, which are presented in Table 3. Women were found to pause more frequently, for longer periods of time, and gazed over a wider range while pausing, than men. No significance was observed on the pause behaviour measures between Gender and Field-of-View. However, similar to the movement behaviour measures, Gender was found to interact with Intelligibility. A significant Gender by Intelligibility interaction was found on pause frequency, $F(1, 92) = 5.103$, $MSE = 128.344$, $p<0.026$, $\eta^2 = 0.055$. As can be seen in Figure 7 and was confirmed by simple effects analysis, men paused more frequently in the high intelligibility environment than the low intelligibility environment, while no significant difference was observed for women ($p<0.163$). A significant interaction between Gender and Intelligibility was also found on the average length of a pause, $F(1, 92) = 4.841$, $MSE = 11.186$, $p<0.030$, $\eta^2 = 0.052$. Presented in Figure 7 is the average pause time data. Simple effects analysis revealed that women paused for significantly longer periods of time in the low intelligibility environment, while men did not show this pattern. Finally, Gender was

Table 3. Cognitive demand measures by gender.

	Gender		
	Female	*Male*	*P-Value*
Pause Frequency	10.29 (0.77)	8.15 (0.81)	P<0.039
Average Pause Time (s)	4.03 (0.31)	3.19 (0.19)	P<0.008
Gaze Range	144.96 (8.23)	118.69 (8.37)	P<0.021

Standard error of means are shown in parentheses.

found to interact with Intelligibility on the range of gaze covered while pausing, $F(1, 92) = 6.041$, $MSE = 18177.510$, $p<0.016$, $\eta^2 = 0.064$, as presented in Figure 7. Simple effects showed that women gazed significantly more in the high intelligibility environment than the low intelligibility environment, while men did not show any significant difference.

A significant three-way interaction was found between Intelligibility, Field-of-View, and Gender on average pause time, $F(1, 92) = 4.578$, $MSE = 10.580$, $p<0.035$, $\eta^2 = 0.049$. The pattern of results for both the constrained and naturalistic field-of-view conditions is presented in Figure 8. In the naturalistic field-of-view condition women paused for a longer period of time than men in the low intelligibility environment than men did, while the reverse pattern was observed in the high intelligibility environment. When the field-of-view was constrained a similar pattern was observed, however the length that women spent paused in the low intelligibility environment increased significantly, while the same did not occur for men.

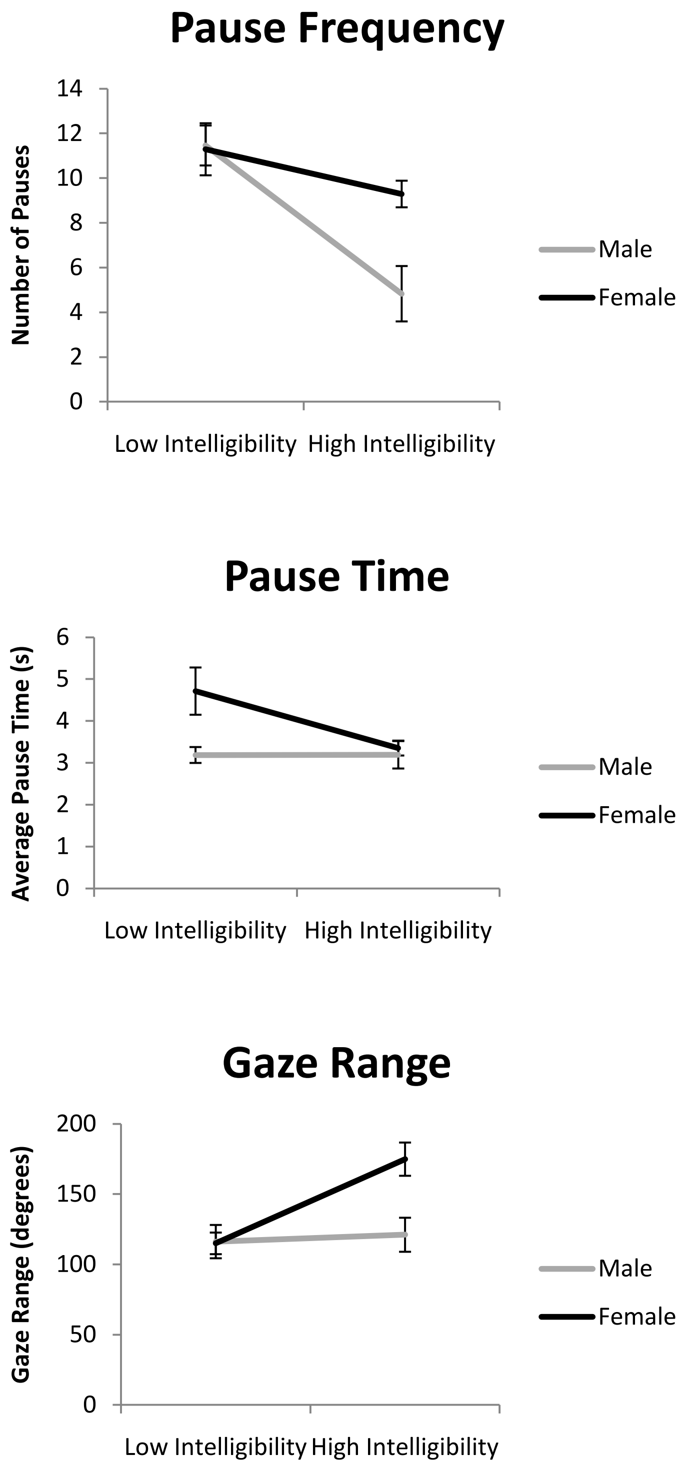


Figure 7. Frequency of pauses, time spent paused, and average gaze range for men and women immersed in high and low intelligibility environments with standard error.

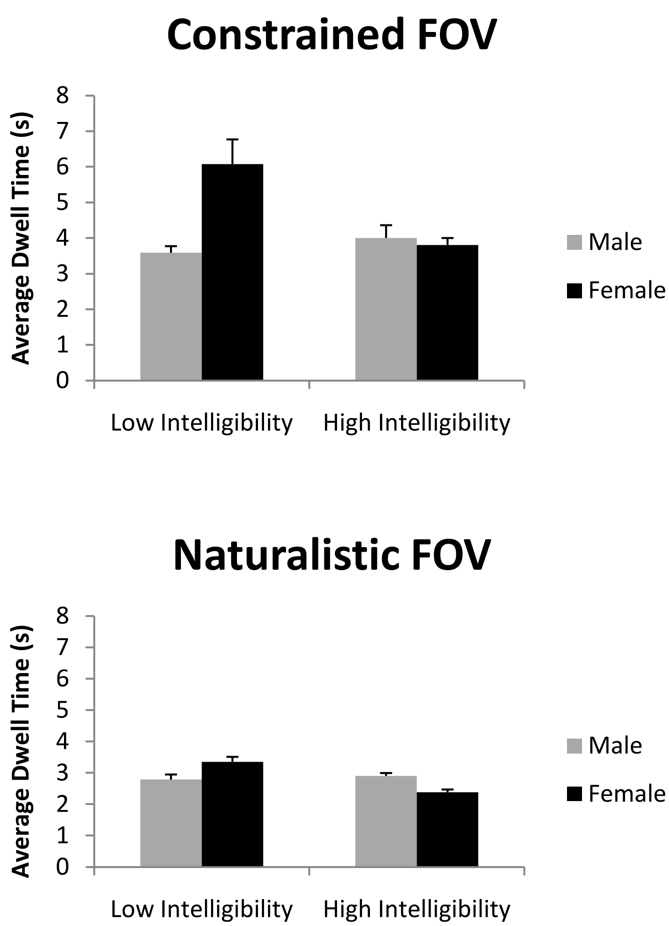


Figure 8. Pause time as a function of gender, intelligibility, and field-of-view with standard error.

1.2.2 Discussion

Experiment 1 successfully replicated the aggregate finding that the configuration of an environment influences wayfinding at the individual level (Dalton, 2001). Participants who navigated through the low intelligibility environment traveled further, took longer to complete the task, and followed more atypical routes from other navigators than did participants in the high intelligibility environment. Additionally, throughout the navigation task, participants paused more frequently and for longer periods of time in the low intelligibility environment. During pauses, participants visually explored the environment less widely when immersed in the low intelligibility environment. Taken together, these results suggest that the complexity with which an environment has been designed can have a profound influence on the way that navigation is performed through the environment. When the environment requires more turns and affords relatively short paths of movement a navigator is more likely to require more time to consider their movements and discourage visual exploration of the local environment as the availability of relational and structural information about the environment is not as readily available.

Gender was found to influence both the movement and pause behaviour measures. Overall, women paused more frequently and for longer periods of time than men in the low intelligibility environment. Additionally, women were found to explore their environment more than men through gazing in the high intelligibility environment. These results support the established gender differences found in the literature (Kimura, 1999) which suggest differential spatial processing mechanisms in women. Women appeared to require more time and visual information in making decisions during the wayfinding task and were less successful than men, traveling further and taking more time to complete the task. This effect was most pronounced in the pause time data, where women paused significantly more in the low intelligibility environment when peripheral vision was also limited. Tentatively, this appears to suggest that women required more processing to parse their surrounding environment into a useful relational account than men, however this statement requires further investigation in order to elucidate the precise mechanism underlying the observed differences.

Interestingly, the limiting of peripheral vision did not appear to influence the wayfinding process as pronounced as that of intelligibility. While limiting field-of-view increased the idiosyncrasy of participant’s routes and caused them to pause for longer periods of time, no influence was found on overall movement time or distance. Past investigations of field-of-view have found decreased performance only at increments below approximately fifty degrees (e.g., Piantanida, Boman, Larimer, Gille, & Reed, 1992; Alfano & Michel, 1990; Chambers, 1982), which is more limited than the field-of-view manipulations used in the current study. Despite the lack of an effect of field-of-view on overall movement behaviour the increased tendency to pause more was consistent with research on decreased field-of-view on a wayfinding task (Lessels & Ruddle, 2004). By constraining field-of-view to sixty degrees, sufficient visual information remains to perform normal wayfinding behaviour was present for the majority of participants. However, the impoverished field-of-view was sufficient to protract planning and decision making performed throughout the wayfinding task.

One account for the lack of a more pronounced effect of field-of-view on overall wayfinding behaviour is that the influence of intersections investigated by Meilinger and his colleagues (in press) was not a consequence of how an intersection affords perceiving more or less visual information about an environment. Furthermore, the consistent and significant effect of intelligibility found in Experiment 1 on virtually all of the measures suggests that the way an intersection affords the perception of the overall configuration of the environment may be responsible for the effect. This would be consistent with investigations which suggest that the angle we approach an intersection at often supports the perception of the most visual information possible (Wiener, Rossmanith, Reichelt, & Franz, 2005), and that it is not the use of the structure of the intersection to determine one's location within an environment or determine an optimal route.

Taken as a whole, Experiment 1 appears to suggest that the influence of spatial configuration on the wayfinding process is not a consequence of constrained peripheral information for the navigator as a result of poorly configured intersections. Instead, the most parsimonious explanation for the observed results is that the influence of intersections (Meilinger, et al., in press) on the wayfinding process is a consequence of a decreased ability for the navigator to ascertain the surrounding environment from their current location, which adversely affects the use of relational information in the wayfinding process.

1.3 Experiment 2

While Experiment 1 successfully demonstrated an effect of the global configuration of an environment on wayfinding behaviour, the weak influence of field-of-view on the measures requires further investigation. A stronger manipulation, investigating whether the established use of configuration in the wayfinding process is a result of either using the local configuration or the global configuration of the environment to elucidate relational information, would be to manipulate this directly. Experiment 2 used an identical task design and dependent measures as Experiment 1; however, instead of manipulating peripheral information, viewing distance was manipulated. Half the participants were able to see the environment normally, while the other half had their vision limited to only the local intersection. This manipulation directly allows the comparison between the use of local configuration to that of global configuration in the established intelligibility effects.

1.3.1 Method

Participants. Forty-eight undergraduate students attending the University of Waterloo participated in the experiment in exchange for course credit. The average age of the sample was 20.12 (SD=1.50). Twenty-four participants were male 19.55 (SD=1.20) and twenty-four female 20.68 (SD=1.78). All participants were fluent English speakers, and had normal or corrected-to-normal vision. Participants who were prone to motion sickness, or had a vestibulocochlear disorder were excluded from participation.

Procedure. Experiment 2 used an identical procedure to Experiment 1, with the following exceptions. First, only one HMD was used due to the insufficiency of the restricted viewing angle to produce an effect on movement behaviour in Experiment 1. The NVIS SX HMD was selected due to its increased resolution marginally increasing the clarity of the visual scene for the vision manipulation in Experiment 2. Second, participants were immersed in either the high intelligibility environment, or the low intelligibility environment. Half the participants navigated with unconstrained vision, while the other half had their vision restricted to the size of an average intersection within the environment plus one standard deviation by fog. This resulted in the participant being able to clearly see to a distance of 49m in high intelligibility environment and 53m in the low intelligibility environment as shown in Figure 9. As the participant moved throughout the environment the fog was shifted around the participant to maintain constant obscuring of viewing distance.

As data in the unconstrained vision condition for both the high and low intelligibility environments was already collected in Experiment 1 no new participants were asked to participate in these conditions. Instead, the data from Experiment 1 was used for the analysis.

Data Analysis. Data was analyzed using identical methods to those employed in Experiment 1. However, participant data for the unconstrained vision condition was derived from Experiment 1 and compared against the forty-eight participants who navigated through the high and low intelligibility environments while having their vision constrained to the local area. Total distance traveled, total task time, number and frequency of pauses, and gaze range while pausing was extracted from the data file for each participant. Path strings were constructed and compared against each other using Leveshtein distance calculations.

1.3.2 Results

Movement Behaviour. Overall movement paths for the low intelligibility and high intelligibility environment for participants with vision constrained to the local area are presented in Figures 10. A 2 (High Intelligibility/Low Intelligibility) x 2 (Constrained

A B

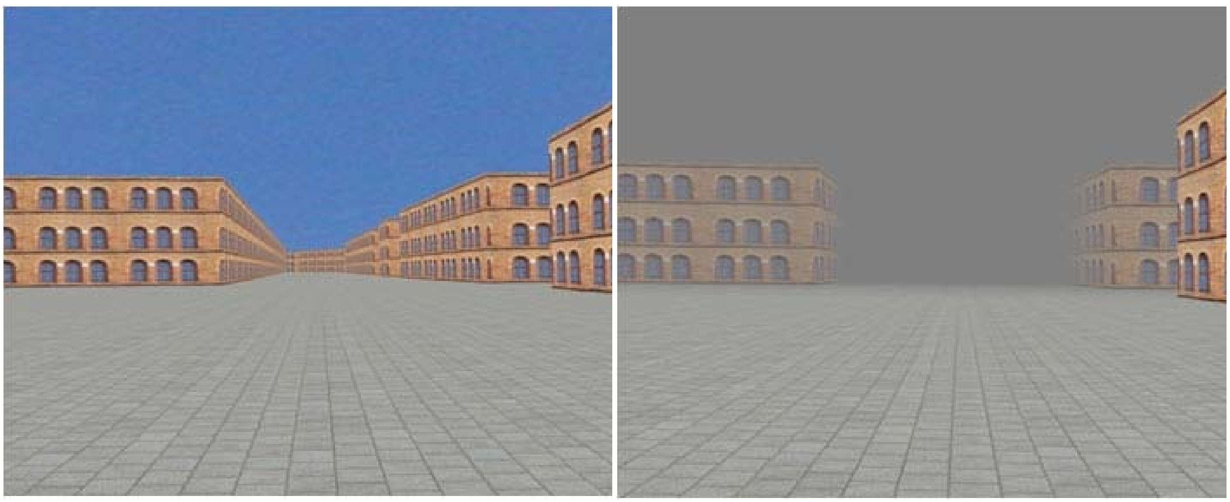
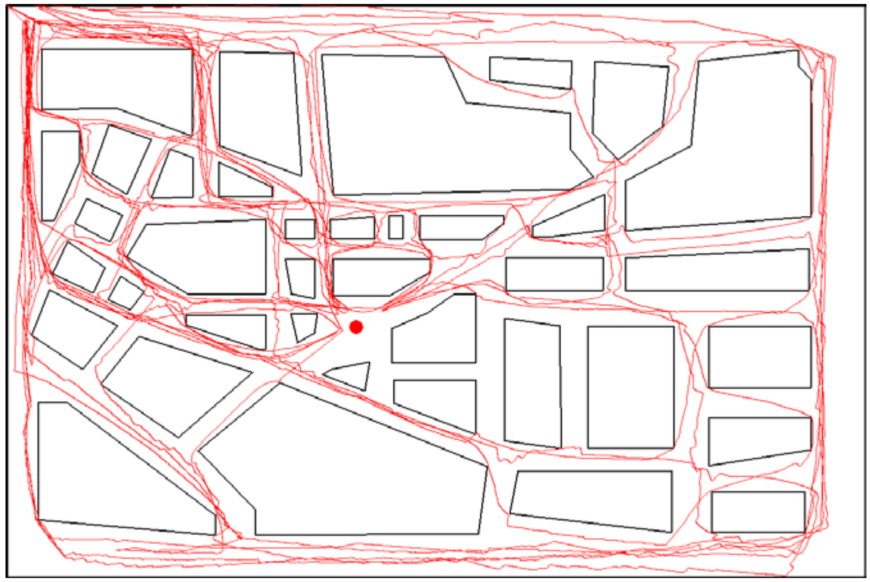


Figure 9. A view of the virtual environment with unconstrained vision (A) and constrained vision, as obscured by fog (B).

A



B

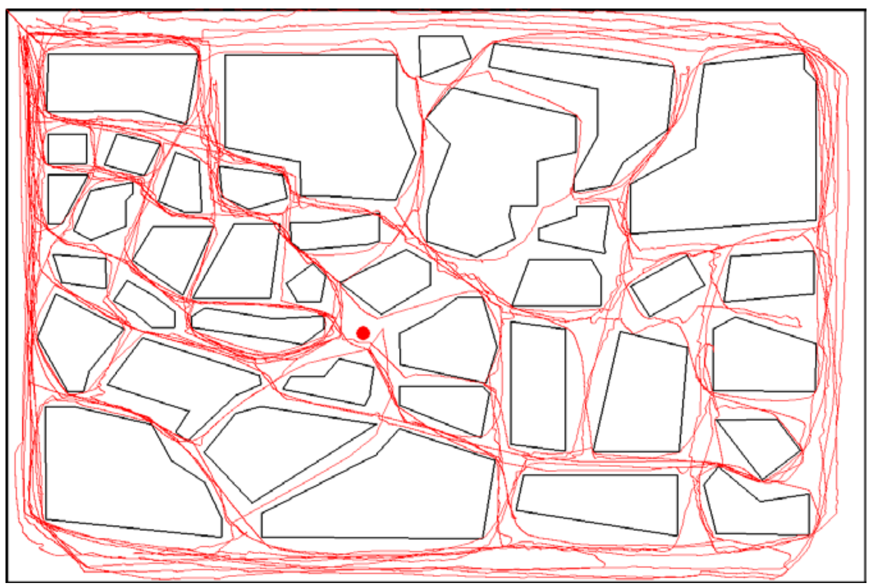


Figure 10. Movement paths for participants in Experiment 2 for the high intelligibility (A) and low intelligibility (B) environments.

Vision/Unconstrained Vision) multivariate ANOVA was performed on the total distance, total time, and path similarity factors.

Similarly to Experiment 1, a main effect of Intelligibility was found on all three movement behaviour variables, confirming the influence of the global configuration of the environment on wayfinding behaviour. A main effect of Intelligibility was found for total time, $F(1, 92) = 23.810$, $MSE = 2382.034$, $p<0.001$, $\eta^2 = 0.213$, total distance, $F(1, 92) = 24.283$, $MSE = 321.703$, $p<0.001$, $\eta^2 = 0.216$, and path similarity, $F(1, 92) = 75.922$, $MSE = 2562.667$, $p<0.001$, $\eta^2 = 0.463$, was found. As can be seen in Table 4, total time and total distance increased in the low intelligibility environment relative to the high intelligibility environment, while path similarity decreased in the low intelligibility environment when compared against the high intelligibility environment.

In contrast to Experiment 1, however, a main effect of Viewing Distance was also found for total time, $F(1, 92) = 23.338$, $MSE = 2334.783$, $p<0.001$, $\eta^2 = 0.210$, total distance, $F(1, 92) = 23.215$, $MSE = 306.360$, $p<0.001$, $\eta^2 = 0.208$, and path similarity, $F(1, 92) = 83.447$, $MSE = 2816.667$, $p<0.001$, $\eta^2 = 0.487$. The results are shown in Table 5. Total time and total distance increased in the constrained vision condition relative to the unconstrained vision condition. Paths were less similar to each other in the constrained vision condition than the unconstrained vision condition. This result supports an account of wayfinding using global configuration rather than that of local configuration. Furthermore, as can be seen in Figure 11, path similarity was found be affected by an Intelligibility through a significant Intelligibility by Viewing Distance interaction, $F(1, 92) = 4.745$, $MSE = 160.167$, $p<0.032$, $\eta^2 = 0.051$. Simple effects analysis found that participants had more similar paths to each

Table 4. Movement Behaviour measures by intelligibility.

	Spatial Intelligibility		
	Low Intelligibility	*High Intelligibility*	*P-Value*
Total Distance (kms)	9.82 (0.90)	6.16 (0.74)	P<0.001
Total Time (s)	27.11 (2.46)	17.15 (2.02)	P<0.001
Path Similarity (Levenshtein distance)	29.33 (1.60)	19.00 (1.69)	P<0.001

Standard errors of means are shown in parentheses.

Table 5. Movement Behaviour measures by viewing distance.

	Viewing Distance		
	Constrained	*Unconstrained*	*P-Value*
Total Distance (kms)	9.78 (0.98)	6.21 (0.64)	P<0.001
Total Time (s)	27.06 (2.69)	17.20 (1.72)	P<0.001
Path Similarity (Levenshtein distance)	29.58 (1.68)	18.75 (1.54)	P<0.032

Standard errors of means are shown in parentheses.

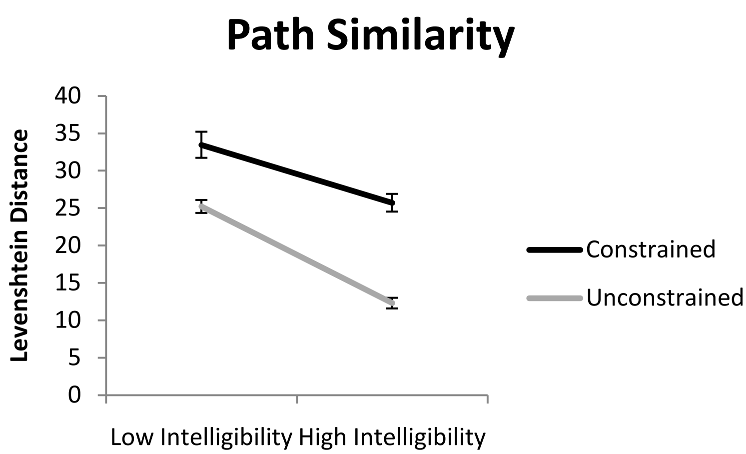


Figure 11. Path similarity under constrained and unconstrained vision in the high and low intelligibility environment with standard error.

other in the unconstrained vision condition than in the constrained vision condition. Paths were also significantly more similar to each other in the high intelligibility environment than in the low intelligibility environment. While an effect on similarity was found, the lack of an interaction with overall distance or task completion time further weakened an account based upon local configuration.

In contrast to Experiment 1, no significant main effects of Gender were found on any of the movement behaviour measures, nor was Gender found to interact significantly with Intelligibility, Field-of-View, or a combination of both factors.

Gaze Behaviour. A 2 (High Intelligibility/Low Intelligibility) x 2 (Constrained Vision/Unconstrained Vision) multivariate ANOVA was performed on the frequency of pauses, average pause time, and gaze range while paused data.

A main effect of Intelligibility was found on gaze range, $F(1, 92) = 17.254$, $MSE = 46200.375$, $p<0.001$, $\eta^2 = 0.164$, but not for the other gaze behaviour variables. Participants gazed over a wider range in the high intelligibility environment (150.44 degrees , SE=8.02) than in the low intelligibility environment (106.56 degrees, SE=6.90). This result reflects the ability for the high intelligibility environment to convey useful visual information relative to the low intelligibility environment.

A main effect of Viewing Distance was found on pause frequency, $F(1, 92) = 4.313$, $MSE = 341.260$, $p<0.041$, $\eta^2 = 0.047$, and average pause time, $F(1, 92) = 7.462$, $MSE = 19.494$, $p<0.008$, $\eta^2 = 0.078$**.** Participants paused more frequently when the viewing distance was limited (number=12.63, SE=1.73) than when it was not limited (number =8.85, SE=0.74). In contrast, the length of pauses was found to show the opposite pattern, with participants pausing for longer periods of time when visibility not constrained to the local environment (4.37s ,SE=0.31) than when it was constrained (3.47s , SE=0.169). Intelligibility and Viewing Distance did not interact significantly. This pattern of results is most parsimoniously explained by insufficient visual information being available to the participants when vision is constrained only to the intersections. Pause frequency increased when visual information was limited, as more frequent examination of the environment was required to maintain wayfinding performance due to impoverished visual information. However, pause time showed the opposite pattern, with longer pauses when vision was not limited to the local environment, as more processing was required to assimilate the available visual information.

A weaker influence of Gender was found in Experiment 2 on pause behaviours. A main effect of Gender was found on pause time, $F(1, 92) = 7.290$, $MSE = 19.046$, $p<0.008$, $\eta^2 = 0.077$, but not for pause frequency or gaze range. Women paused for longer periods of time, on average, (4.36s, SE=0.32) than did men (3.47s, SE=0.18). Gender was not found to interact with Viewing Distance, but a trending interaction between Gender and Intelligibility was observed for gaze range (Figure 12), $F(1, 92) = 3.498$, $MSE = 276.760$, $p<0.065$, $\eta^2 = 0.038$. However, due to a lack of significance, simple effects analysis was unable to identify which group gazed more widely, though women did show trend towards significance.

A significant three-way interaction was found between Intelligibility, Viewing Distance, and Gender, $F(1, 92) = 11.200$, $MSE = 29.260$, $p<0.001$, $\eta^2 = 0.113$, on time, as presented in Figure 13. Simple effects showed men paused for significantly less time in the low intelligibility environment than they did in the high intelligibility environment, with the reverse pattern being observed for women when vision was not limited. When vision was constrained the reverse pattern was found, with women pausing for less time in the low

Figure 12. The gaze range of male and female participants for both the high and low intelligibility environments with standard error.

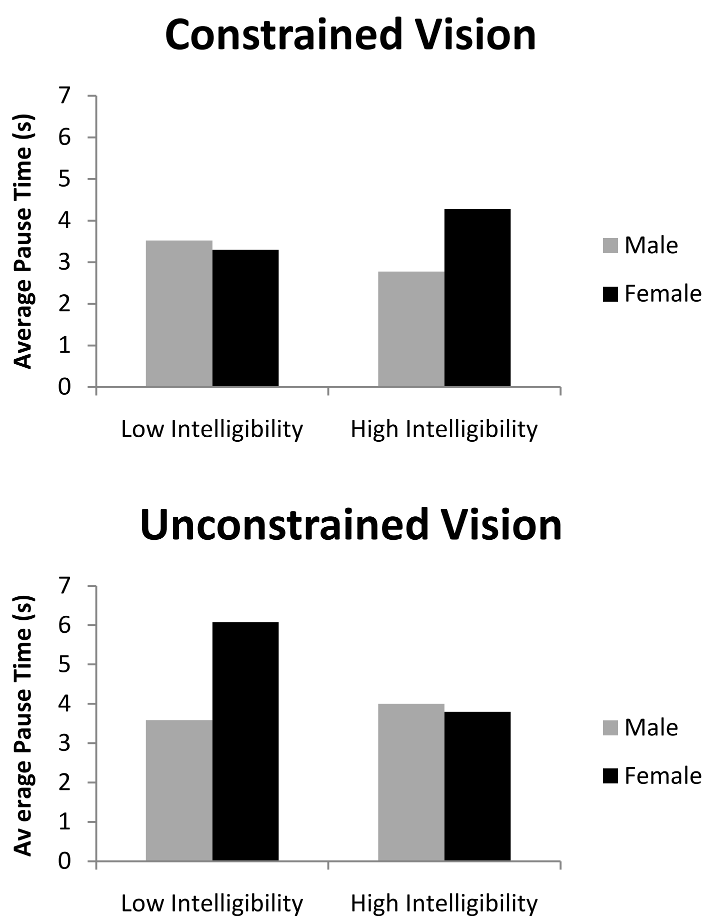


Figure 13. Average pause time as a function of gender, intelligibility, and field-of-view with standard error.

intelligibility environment than they did in the high intelligibility environment, with the reverse being observed for men. While this pattern is similar to that found in Experiment 1 with unconstrained peripheral vision, though markedly more pronounced, the finding that pause time showed the reverse when vision was constrained was not predicted. This pattern of results provides some evidence for an attempt to assimilate configurational information, especially in the high intelligibility environment, but with decreased viewing distance making this more difficult. Taken with the results of Experiment 1 these results may provide further evidence that women are marginally less efficient at integrating relational information based on the structure of an environment.

1.3.2 Discussion

As with Experiment 1, Experiment 2 demonstrated the powerful influence of global spatial configuration on the efficiency of navigation through an environment. Participants navigated less efficiently through the low intelligibility environment than in the high intelligibility environment, traveling further and taking longer to complete the task. Additionally, participants were less likely to follow similar paths to those of other navigators in the low intelligibility environment when compared to the high intelligibility environment. Participants were found to gaze more in the high intelligibility environment than in the low intelligibility environment, reflecting an acquisition of the information afforded by a highly intelligible configuration. However, unlike Experiment 1, the number of pausing and frequency of pausing did not differ significantly between the two environments. This failure to replicate the result is best explained by the interaction with Viewing Distance, whereby the reverse pattern of results was observed for pause times between unconstrained and constrained vision, suppressing any significance, and therefore represents an artefact of the experimental manipulation used in Experiment 2.

Gender effects were categorically less pronounced in task performance in Experiment 2. While Gender continued to show an interaction with intelligibility on the length of time that pauses were engaged in for women, a significant effect on the frequency or pattern of gaze was not observed, also potentially influenced by the Viewing Distance manipulation. An alternative explanation for the different pattern of results could be that the observed gender effects were a product of some unidentified individual difference, given the inconsistency of studies in reproducing gender differences across a variety of wayfinding paradigms (Coluccia & Louse, 2004). However, as the increased decision time for women as a function of the availability of global configuration information did persist in Experiment 2, this account is considered to be less likely. Instead, the observed results, especially in the context of pause times suggest potential evidence for different gender performance in the acquisition of relational information.

More interestingly, the contrasting effect of the visual manipulations in Experiment 1 and 2 provide strong evidence for an account which postulates that the relational information afforded by perception of the global configuration of an environment is necessary in order to maintain optimal navigation. When vision was constrained to that of the local intersection, participants demonstrated performance comparable to that of participants in the low intelligibility environment, especially prevalent in the movement behaviour data. The inability to perceive the global structure further exacerbated the idiosyncratic nature of a participant’s chosen route, with participants showing less similar paths when vision was constrained than when vision was not limited, with the difference in paths maximized in the low intelligibility environment. Parsimoniously this pattern of results argues strongly in favour of an account of the importance in perceiving relational information about an environment through both efficient design and ideal environmental conditions.

1.4 General Discussion

Experiment 1 investigated the influence of impoverished peripheral information on the use of global structural information in two novel environments and found a strong influence of the structure of an environment regardless of the availability of peripheral vision. Participants took longer to complete the wayfinding task, traveled further overall, and followed my idiosyncratic routes in the less intelligible environment than they did in the high intelligibility environment. Participants were also found to gaze around the environment less in the high intelligibility environment, as well as paused for a longer period of time. These results were consistent with an account of the use of relational information determined from the global structure of the environment, determined particularly from distant rather than global perceptual features. Experiment 2 more directly investigated this finding by allowing either unlimited or constraining the distance with which participants could see throughout the wayfinding task. Similar effects of configuration were observed to Experiment 1, with participants navigating less efficiently in the low intelligibility environment relative to the high intelligibility environment, however differences in pause behaviour was not observed. One potential explanation for this inconsistency is that the field-of-view manipulation eliminated the ability to detect any differences. Surprisingly, limiting viewing distance was found to result in similar movement behaviour as that of low intelligibility providing further evidence that humans navigate using relational cues based on the distal configuration of an environment rather than based on local intersections or their ability to affect the perceptual process.

Throughout both Experiment 1 and Experiment 2 pause time, frequency, and gaze range was found to be affected by both visual manipulations with varying effect sizes. In general, gaze behaviour was widest when the environment afforded more opportunities to perceive the structure of the environment. This finding is consistent with Conroy (2001) as well as those of the current study which suggest that processing of the relational structure of an environment does involve some effort and is not necessarily as effortless as has been suggested in a recent review (Penn, 2003).

Gaze behaviour was the most consistent behaviour during pauses to be observed across both experiments. When the environment was highly intelligible gazing was found to be wider, on average. This is consistent with the theoretical mechanisms underlying the relational measures of space syntax and their axial maps which argue that navigation is largely a product of the use of most enhanced lines-of-sight (Hillier, 1996), rather than pure dependence on landmarks and learned routes. When examined in the context of pause behaviour and overall movement behaviour observed in both experiments, this finding in a striking example of the examination of the configuration of space throughout a wayfinding endeavour.

Several interesting Gender effects were observed across both experiments with women generally showing an increased tendency to pause, travel further, and visually examine the environment more than men. While the current studies are unable to determine the reason for these differences they most likely represent a difference in spatial processing which has been found in other studies of gender and wayfinding (Kimura, 1999). Further study is necessary to elucidate the precise mechanisms underlying this observed difference.

1.4.1 Implications for Spatial Cognition

The consistent finding at the individual level found in both the present investigation and those of Conroy (2001), that the structure of an environment and the way it affords relational information about the overall configuration of an environment can influence wayfinding decisions, should not be understated. The information perceived through the observation of the environment as a whole is clearly an important determinate of route choice. While the acquisition and use of relational structural information about an environment needs further investigation, several investigations have suggested that this knowledge is used in a synergistic fashion with other knowledge, such as that of landmark knowledge (Newman, Caplan, Kirschen, Korolev, Sekuler, & Kahana, 2007; Stankiewicz & Kalia, 2007). Newman and colleagues (2007) had participants make their way from one position within an environment to another in the most efficient way possible across a number of trials. Several environments were used which varied the number of landmarks present. The authors determined that the layout of an environment was sufficient for participants to determine optimal routes to a location. However, by manipulating the presence of landmarks the authors were further able to determine that the presence or absence of landmarks could further enhance or inhibit performance, respectively. While these investigations did not directly manipulate the complexity of the environment's configuration, they do suggest an implicit use of configuration or relational knowledge in the wayfinding process.

Some evidence suggests that the parahippocampal gyrus may support this acquisition and integration process (Aguirre, Zarahn, & D'Esposito, 1998). Damage to the parahippocampal gyrus has been shown to result in profound difficulty orienting within an environment (Aguirre & D'Esposito, 1999; Aguirre, Detre, Alsop, & D'Esposito, 1996). This phenomenon, known as topographical disorientation, provides potential further support for the use and integration of configuration knowledge. When the information is lost or cannot be acquired, profound disorientation may be experienced by an individual.

1.4.2 Future Directions

At present, the interaction between landmark and relational knowledge is relatively poorly understood. It is unclear how the presence of a landmark or other acquired knowledge about an environment can influence the seemingly implicit use of configuration throughout the wayfinding process. Specifically, the degree to which a route considered to be efficient based on relational information, such as well-connected and well-integrated paths, is used once landmark knowledge has been acquired about an environment bears further investigation. One method to investigate this phenomenon could expose participants to one of several environments with different levels of intelligibility on multiple occasions, while progressively increasing the complexity of the routes in which the participant is required to be engaged. As the participant becomes more familiar with the environment, landmark knowledge would increase, while knowledge about the structure of the environment would remain stable. Based on the results of this study, I would expect that landmarks would be used in order to navigate to paths considered to be optimal based upon relational information.

1.4.3 Conclusion

In conclusion, the present study showed a strong influence of spatial configuration on the wayfinding process, with limited use of the local visual environment. The failure to find an effect of the local visual environment suggests the use of relational configuration knowledge is based on direct perception of the distant environment. Further study is necessary to investigate the acquisition and relative weighting of both relational knowledge and landmark knowledge, as well as determine the neural substrates.

References

Alfano, P. L., & Michel, G. F. (1990). Restricting the field of view: Perceptual and performance effects. *Perceptual and Motor Skills, 70,* 35–45.

Aguirre, G.K. & D'Esposito, M. (1999). Topographical disorientation: a synthesis and taxonomy. *Brain*, 122(9), 1613-1628.

Aguirre, G.K., Detre, J.A., Alsop, D.C. & D'Esposito (1996). The parahippocampal gyrus subserves topographical learning in man. *Cerebral Cortex*, 6(6), 823-829.

Aguirre, G.K., Zarahn, E., & D'Esposito, M. (1998). Neural components of topographical representation. *Proceedings of the National Academy of Science*, 95, 839-846.

Benedikt, M.L. (1979). To take hold of a space: isovists and isovist fields. *Environment and Planning B*, 6, 47-65.

Chambers, W. W. (1982 April). *Visual technology research simulator: Flight simulation avionic systems and aero medical aspects.* Presented at the Royal Aeronautical Society's Flight Simulation Symposium, London.

Coluccia, E. & Louse, G. (2004). Gender differences in spatial orientation: a review. *Journal of Environmental Psychology*, 24(3), 329-340.

Conroy, R.A. (2001). Spatial navigation in immersive virtual environments. *Unpublished Doctoral Thesis*. Department of Architecture, University College London.

Conroy-Dalton, R.A. (2003). The secret is to follow your nose: route path selection and angularity. *Environment and Behavior*, 35(1), 107-131.

Haq, S. (1999). Can space syntax predict cognition? *Proceedings of the Second International Space Syntax Symposium, II* (40.1-40.14). Brasilia, Brazil: Universidad de Brasil.

Hillier, B. (1998). A note on the intuiting of form: three issues in the theory of design.

Environment and Planning B, 26, 169-191.

Hillier, B. (1996). Space is the machine. Cambridge: Cambridge University Press.

Hillier, B., Burdett, R., Peponis, J., & Penn, A. (1987). Creating life, or, does architecture determine anything? *Architecture and Behaviour,* 3, 233-250.

Hillier, B. & Hanson, J. (1984). The social logic of space (Paperback Edition 1988). Cambridge:

Cambridge University Press.

Hillier, B. & Hanson, J. (1987). Ideas are in things: an application of the space syntax method to discovering housing genotypes. *Environment and Planning B*, 14, 363-385.

Hillier, B., Penn, A., Hanson, J., Grajewski, T.,&Xu, J. (1993). Natural movement; or, configuration and attraction in urban space use. *Environment and Planning B: Planning and Design*, *20*, 29-66.

Kim, Y.O. & Penn, A. (2004). Linking the space syntax of cognitive maps to the spatial syntax of the environment. *Environment and Behavior*, 36(4), 483-504.

Kimura, D. (1999). *Sex and cognition.* Cambridge, MA: MIT Press.

Lee, T. (1970). Perceived distance as a function of direction in a city. *Environment and Behavior,* 2, 40-51.

Lessels, S. and Ruddle, R.A. (2004). Changes in navigational behaviour produced by a wide field of view and a high fidelity visual scene. In: Coquillart, S. and Göbel, M., (eds.) *Proceedings of the 10th Eurographics Symposium on Virtual Environments*, Grenoble, France: June 8 - 9, 2004, pp. 71-78.

Levenshtein, V.I. (1965). Binary codes capable of correcting deletions, insertions, and reversals. *Doklady Akademii Nauk SSR (Russian)*, 163(4), 645-848.

Lynch, K. (1960). The image of the city. Cambridge: Joint Center for Urban Studies.

Meilinger, T., Franz, G., & Bülthoff, H.H. (in press). From isovists via mental representations to behavior: first steps toward closing the casual chain. *Environment and Planning B: Planning and Design*.

Meilinger, T., Knauff, M., & Bülthoff, H.H. (2008). Working memory in wayfinding – a dual task experiment in a virtual city. *Cognitive Science*, 32(4), 755-770.

Newman, E.L., Caplan, J.B., Kirschen, M.P., Korolev, I.O., Sekuler, R., & Kahana, M.J. (2006). Learning your way around town: how virtual taxicab drivers learn to use both layout and landmark information. *Cognition*, 104(2), 231-253.

Piantanida, T. P., Boman, D., Larimer, J., Gille, J., & Reed, C. (1992). Studies of the field-of-view/resolution tradeoff in virtual reality. In *Proceedings of the SPIE: Human Vision, Visual Processing and Digital Display III* (Vol. 1666, pp. 448–456). Bellingham, WA: SPIE-The International Society for Optical Engineering.

Penn, A. (2003). Space Syntax and spatial cognition: Or why the axial line? *Environment and Behavior*, 35, 30-65.

Penn, A., Hillier, B., Banister, D., & Xu, J. (1998a). Configurational modeling of urban movement networks. *Environment and Planning B: Planning and Design, 25*, 59-84.

Penn, A., Hillier, B., Banister, D., & Xu, J. (1998b). Configurational modeling of urban movement networks. In J. Ortuzar, D. Henshar, & S. Jara-Diaz (Eds.), *Travel behavior research: Updating the state of play* (pp. 339-362). Elmsford, NY: Pergamon.

Peponis, J., Hadjinikolaou, E., Livieratos, C., & Fatouros, D.A. (1989). The spatial core of urban culture. *Ekistics*, 334, 335 Jan-Feb, Mar-Apr, 43;55.

Peponis, J., Zimring, C., & Choi, Y.K. (1990). Finding the building in wayfinding. *Environment and Behavior*, 22(5), 555-590.

Prestopnik, J. L., & Roskos-Ewoldsen, B. (2000). The relations among wayfinding strategy use, sense of direction, sex, familiarity, and wayfinding ability. *Journal of Environmental Psychology*, 20, 177–191.

Ratti, C. (2004). Space syntax: some inconsistencies. *Environment and Planning B: Planning and Design*, 31(4), 487-499.

Sandstrom, N.J., Kaufman, J., & Huettel, S.A. (1998). Males and females use different distal cues in a virtual environment navigation task. *Cognitive Brain Research*, 6, 351-360.

Stankiewicz, B.J. & Kalia, A.A. (2007). Acquisition of structural versus object landmark knowledge. *Journal of Experimental Psychology: Human Perception and Performance*, 35(2), 378-390.

Tan, D.S., Czerwinski, M.P., & Robertson, G.G. (2006). Large displays enhance optical flow cues and narrow the gender gap in 3-D virtual navigation. Human Factors, 48(2), 318-333.

Wiener, J.M., Rossmanith, N., Richelt, A., & Franz, G. (2005). Isovists capture locomotion-relevant properties of space. In: Bülthoff, H. H., K. R. Gegenfurtner, H. A. Mallot, R. Ulrich and F. A. Wichmann (eds.) *Proceedings of the 8th Tübingen perception conference*, 3185, Kirchentellinsfurt, Germany: February, 2005.