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Examining the Effects of Sequential Polyhedron Visibility on Wayfinding and Evacuation

An Online Experiment in Virtual Reality Environment

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ABSTRACT

The paper presents the understanding the basics of the human wayfinding process that can be substantially illuminated by the correlations between space-syntactic variables and kinesthetic data of individuals roaming in a spatio-temporal environment. However, two-dimensional syntactic concepts offer a perception of place to some extent, they may neglect to capture the volumetric effects of space on human perception, especially during movement. Therefore, besides 2D syntactic variables, this paper essentially focuses on polyhedrons as 3D isovists to explore the impacts of the sequential volumetric visibility data on human behavior in terms of the spatial decision-making process in the wayfinding and evacuation issues. In this framework, the article discusses the results of a series of wayfinding and evacuation experiments implemented in a virtual building environment consisting of randomly arranged and dimensioned circulation areas. While evacuation experiments contained legal egress signages at properly designated doors and spots, wayfinding experiments had no signboards. On the other hand, the 3D building model is designed with a couple of architectural modeling software and transferred into a simulation environment. The experiments are conducted with forty four (44) respondents over an online meeting platform. Then, the respondents' trajectories and kinesthetic data are retrieved from the experiments, and the correlations between behavioral and syntactic data are investigated. The primary findings demonstrated that participants in the regular exit group tended to be around the zones with higher integration values. In contrast, the signages and volumetric visibility data are highly influential on the emergency exit group when evacuating the building.

KEYWORDS

Environment-Behavior Studies, Space Syntax, Volumetric Space, Wayfinding, Evacuation

1 INTRODUCTION

Human perception plays a vital role in the wayfinding issues, and sight is one of the most prevailing senses during human movement. In this way, people can perceive and get visual information, bear in mind, and compare it with other sensory data which is previously accumulated and obtained experiences. Thus, human beings can decide which direction to move in physical environments. Although ongoing investigations do not fully explain this action, we still have strict arguments about how different spatial features are perceived and interpreted by people and how these spatial properties affect decision-making processes while people find their ways. Therefore, cognitive researches that can shed light on this subject has critical importance, specifically for a discipline such as architecture, directly related to environment-behavior relations.

Space Syntax Theory is one of the prominent research fields that examine environment-behavior relations within the framework of the architectural discipline. The theory asserts that universally accepted quantitative and syntactic analysis methods may explain human perception. In this framework, Benedikt (1979) put forward substantial studies on the concept of 'isovist' by describing and formulating some isovist properties such as the area, perimeter, and circularity. As the visible field from a specific vantage point, isovist can be conceived as the two-dimensional planar representation of the three-dimensional environment with minimal loss of spatial information (Benedikt 1979). Although many related and illuminating investigations examined human behavior within the physical surroundings, the issue of spatial information loss being as low as possible can be considered a highly controversial argument. Ünlü et al. (2019) argue that although planar representations provide information about space and spatial perception, two-dimensional parameters are limited in explaining the volumetric space.

The polyhedrons can represent the three-dimensional visibility space accurately; therefore, as the generator of volumetric visibility data, the polyhedrons may be essential for comprehending the spatial behaviors in wayfinding issues. However, besides these syntactic parameters, it is also highly crucial to consider the dimension of time in cases of human perception. Batty (2001) expresses that spatial perception can change with variations in the isovist parameters while people are in motion. Accordingly, each moment in every specific node may lead to differentiation in human perception and even in the spatial decision-making process in wayfinding. Therefore, besides 2D syntactic variables, this paper mainly investigates the effects of the volumetric visibility properties such as polyhedron volume, polyhedron surface area, and spherical circularity in the wayfinding issues through sequential and syntactic measurements.

This research presents two different experimental studies to investigate. Both experiments were realized in the virtual environment and conducted through online meetings. In this simulation research, participants could roam freely in the virtual building. In the first of these experiments, one-half of the participants were assigned to go to the exit doors from a certain point in the building. In the second, the other half of the attendants were asked to find the emergency exit doors from another location in the building. While there were emergency exit signages in the emergency evacuation experiment, there were no guiding signs in the regular wayfinding experiment. In both experiments, the starting points of the participants were determined as the deepest points according to the exit and emergency exit doors. Accordingly, the effects of the signs on peoples' spatial perception and wayfinding processes were also explored within the scope of this article. During the analysis phase of the study, the trajectories of the respondents were collected, and the correlations between syntactic and behavioral data were evaluated as subjective, objective, and sequential objective assessments.

2 THEORY

The concept of isovist may be described as the polygonal two-dimensional representation of all visible areas from a particular observation point (Dalton and Dalton 2001). An isovist can be evaluated in two sub-categories: isovist and radial data. Isovist data is related to the measurements of the features based on the geometric form of the isovist polygon (Benedikt 1979). On the other hand, radial data deals with the comparisons or changes of the lengths of the rays thrown from the observer's point to the surroundings (Batty 2001). These rays as radials play a role in creating the concept of the isovist. In this context, Benedikt (1979) asserts that numerical values may represent certain human perceptual and cognitive factors related to specific isovist properties.

On the other hand, isovist fields can be expressed as diagrams where the isovist values are calculated and demonstrated simultaneously for every possible observation point in the space (Benedikt, 1979). Similarly, Turner et al. (2001) also posit the 'visibility graph' concept by looking at the area units and their neighborhood relations in each observation point within the other neighboring vantage points. These syntactic diagrams give a holistic idea about the spatial configuration regarding the isovist or radial data values in the building or urban scale. Eventually, Franz and Wiener (2005) investigate the empirical studies about isovists regarding human behavior and state that isovist is an observer-centered model capable of capturing environmental features related to spatial behavior and experience.

Hillier and Hanson (1984) express that mutually interrelated spatial and social hierarchical orders reflect each other, and these interconnections may be revealed with the 'justified graph maps' as graphical expressions (p. 154). The concept of depth levels within the framework of graph data and calculated mean depth concepts are key concepts in justified graphs. While the depth can be defined as the visual distance of a place from any other point in the justified map, the mean depth indicates the average of depth levels from all other locations in the space. Moreover, the concept of integration can be explained as a normalized version of the inverse of the mean depth.

Normalizing the mean depth values enables researchers to compare various spatial layouts syntactically. In this context, the integration value of the space illustrates how the area is integrated or segregated compared to other zones in the surrounding. Peponis et al. (1990) argue the integration value might be closely related to the spatial patterns in wayfinding.

In the framework of the 3D isovist issue, Gewirtzman et al. (2005) state that “A 2D visual analysis cannot capture the whole 3D situation and get close to the human perception.” (p. 24). In addition, Yang et al. (2007) reviewed previous researches about the 3D isovist approaches and concluded that these methods reflect the human perception of space better than the 2D approaches. Although the concept of 2D isovist may syntactically analyze spatial properties in wayfinding issues in a sense, it remains quite abstract by missing the spatial information to a great extent by omitting the volumetric features that they reversely may attract people’s attention in wayfinding (Bhatia et al. 2013). Varoudis and Psarra (2014) also defend three-dimensional visibility during human movement in this sense. They emphasize its essential role in the architectural experience and its effective expression about how people observe and comprehend spatial and visual connections while physically reaching these interactions. Ünlü et al. (2019) mention that volumetric values and polyhedron structure of the sight concerning parameters such as width, height, and depth of the vantage point in an architectural space might be influential in the wayfinding process.

From this point of view, Turner et al. (2001) mentioned that Benedikt has envisioned polyhedrons and taking a slice of this volume in the horizontal plane to define the concept of isovist as the simplified version of presented space. Recently, Ünlü et al. (2019) focused on the concept of the polyhedron and expressed the importance of these forms in visual affordance, especially for understanding the potentials of the effect of three-dimensional volumes in wayfinding. Thus, the polyhedron concept might be conceived as one of the primary syntactic measurands to capture spatial perception through geometric and radial data values, just as Benedikt’s isovist concept. In this context, this article defends that the concept of three-dimensional volume as polyhedrons might represent themselves as the essential measurand in syntactic analyses.

There are various methods for creating the 3D isovist application forms, which some of these may be produced with the spherical projection method (Gewirtzman et al. 2003) or 360º rotation of the two-dimensional isovist form (Yang et al. 2007) or calculations based on voxel-based neighborhood relations (Morello and Ratti 2009) or the scatter of the rays through the three-dimensional surroundings (Bhatia et al. 2013). Each method for obtaining the 3D isovist may have competence in investigating specific syntactic values and reveals a suitable calculation method. For example, the concept of the ‘Spatial Openness Index’ (SOI), which is put forward by Gewirtzman et al. (2003), describes the observer's perception of spatial density, so SOI is calculated by dividing the visible volume by the surface area of the 3D isovist. The spherical projection method has been sufficient in creating the 3D isovist, especially for this process.

In the scope of the Space Syntax Theory, many wayfinding experiments are conducted at the urban and the building scales. The experiments are conducted by Peponis et al. (1990) can be counted among one of the significant studies in this field. In these experiments, the correlation between the participant's wayfinding success and integration values of spaces of a hospital building was examined. As a result, these researchers revealed that the participants are tended to be in places with higher integration values during the wayfinding process. Surprisingly, these participants have also had difficulties in case of finding their ways around some of these highly integrated points. Consequently, these researchers remarked that the complex buildings should be designed concerning syntactic properties, and their circulation areas should be supported by guiding signages.

O'Neill's (1991) experiments in a university campus library building also have significant results in this discussion. This study has revealed that the increase in topological complexity in environments, especially without signages, may cause difficulties in comprehending spatial organization. Thus, topological complexity entails wayfinding problems, and reaching the destination takes a long time, especially in complex environmental organizations. In this frame, Haq and Zimring (2003) also point out that spatial order directs human movement, lets people understand the spatial characteristics, and shows better performances in wayfinding due to this motion.

There are also simulational experiments conducted in virtual environments. Mavridou et al. (2009) conducted a simulation experiment on the urban scale, and they examined the effects of integration and building heights, especially in wayfinding. As a result, they mentioned that the main factor for people in their orientation is the integration values and that the building heights are ineffective in wayfinding. However, if there are guiding signages on the predetermined routes, the effects of the integration as graph data may also be reduced, especially in the wayfinding evaluations (Natapov and Gewirtzman 2016).

Human beings live in the spatio-temporal world that is in constant motion. External environmental factors continuously change the mood even if people are not in motion. Every moment contains a wide variety of information for the individual. Every millisecond may considerably impact spatial behavior and human perception. Therefore, obtaining perceptual data as much as possible about these moments may be essential in conducting experimental studies such as wayfinding and evacuation. Gewirtzman et al. (2003) also argue that people's time experience is significant in the observer's perception and the evaluation of their environment. In this way, as the two-dimensional representations of volumetric fields may not wholly reflect the volumetric features of the physical surroundings, steady syntactic analysis methods may also omit to capture and monitor instantaneous spatial behaviors. Within the developments in computer technologies, the cognitive values related to human perception and spatial behavior can be evaluated instantly, especially by simulation experiments.

3 DATASET AND METHOD

Besides the correlations between 2D syntactic and kinesthetic data, this paper mainly examines the relations between volumetric visibility properties and the spatial behaviors during wayfinding and evacuation processes. In this context, two different experimental studies are designed as one for wayfinding and one for evacuation issues. These experiments occur in a virtual building. While eighteen (18) people accomplished the wayfinding experiment, the same amount of people (18) completed the evacuation experiment. Furthermore, a series of algorithms were created to obtain the participants' trajectories to measure the 2D syntactic data, 3D syntactic data, and kinesthetic data dynamically and statically. These algorithms are prepared with the Grasshopper, a plug-in software of the Rhinoceros 3D.

The study focuses on these 2D and 3D syntactic data as isovist area, isovist perimeter, drift, circularity, standard deviation, variance, skewness, depth, mean depth, integration, polyhedron volume, polyhedron surface area, optimized polyhedron volume, optimized polyhedron surface area, and spherical circularity. In addition, participants' personal data are collected as gender, age, education level, profession, and computer gaming experience. On the other hand, these kinesthetic data are also investigated as body movement's frequency of interpasses, frequency of stepbacks or stops, frequency of turns, frequency of head rotations, frequency of unmatched movement and looking directions, and others; as time spent in nodes, duration of stops, passed distance, duration, and average speed. These data are evaluated under the categories such as objective assessments, subjective assessments, and sequential objective assessments.

The spatio-temporal world provides people with infinite variety and size of volumetric spaces. Therefore, a highly complex virtual building is designed for the experiments. This model contains circulation areas with many different spatial dimensions, and it aims to reflect diverse syntactic features to capture various spatial behaviors. The design of this architectural model is created by using Rhinoceros 3D and Grasshopper (Figure 1).

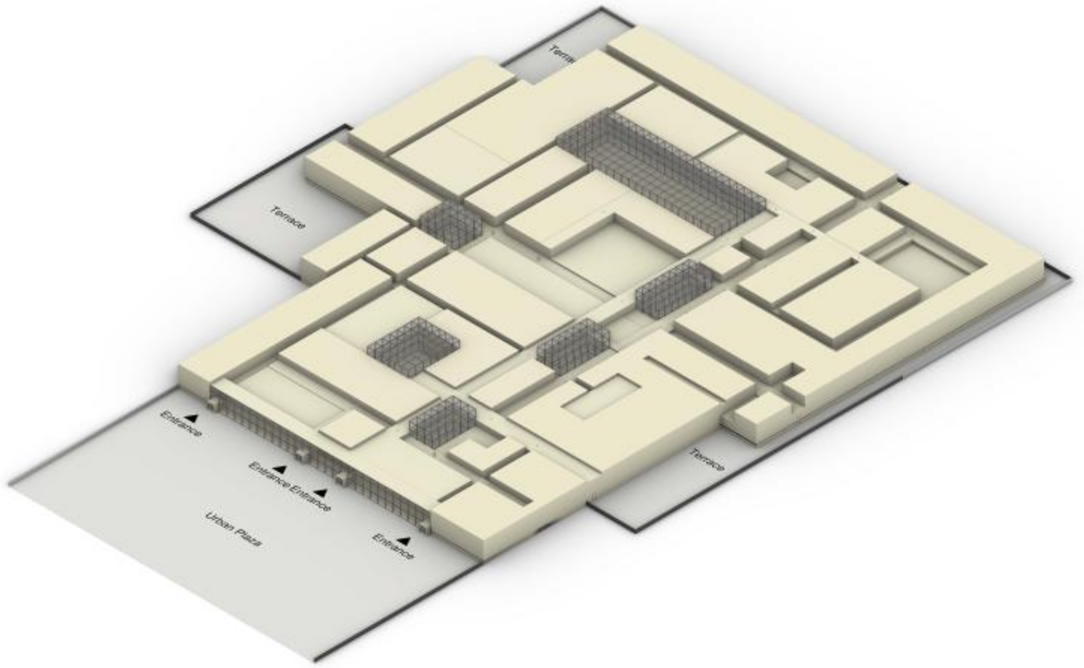


Figure 1: The 3D Building Model

The plan of the one-story building is created with Grasshopper and its plug-in Magnetizing Floor Plan Generator (Egor et al. 2020). What this plug-in does, in general, might be defined as fitting the desired number of rooms and halls into a particular area within a simple architectural understanding while taking into account the square meters specified for these spaces and the neighborhood relationship between these spaces. Then, random widths are assigned to each corridor limited by random sizes between 1,5m and 4,5m. The corridor and hall heights are also created with random altitudes between 3m and 6m. Consequently, the virtual building model has 16230m² total area and has a circulation area of 6335m² with 55 nodes.

The egress doors and signages in the building are located considering National Fire Protection Association (NFPA 101) standards, especially for the evacuation experiments. After the generation of the building model, the room and exit doors are added. The facade at the building entrance hall and walls of the inner courtyards are designated as the glass curtain wall. In this context, the effect of the spatial light on the spatial behavior of people is ignored. After that, the doors at the appropriate points in the circulation areas are assigned as emergency exit doors. In this context, the exit doors are also counted as emergency exit doors in the emergency exit experiments. In addition, emergency exit signs are added to every node and other required points in the circulation areas. The egress signs are also placed on the emergency exit doors. The dimensions of all emergency exit signs are sized to be 18x45cm. While the emergency exit signs in the circulation areas are positioned at 240cm height, the signages above the egress doors are located at 210cm height.

Experimental studies in wayfinding issues as computer simulations might be conducted in three different methods. The first is the applications in which certain moments in a virtual space are displayed on the computer screen as photographic frames, as applied by Wiener et al. (2007). The second is the experiments in which participants move freely in the simulation environment monitored by the computer screen, as demonstrated by Stamps (2009). The third is the studies in which the participants can freely navigate the simulation environment provided by virtual glasses, as shown by Shushan et al. (2016). Cha et al. (2019) mention that participants perceive and experience spatial features more intensely in simulation experiments performed through virtual glasses. Nevertheless, this study focuses on the second method because of the lockdowns and social distance issues due to the pandemic conditions, which entailed difficulties in having face-to-face meetings to conduct the experiments with participants.

In this context, the computer simulation is created with Unity and Microsoft Visual Studio software. First, the building model is imported into the Unity software. Here, an avatar is created. This avatar allowed participants to roam freely and observe the simulation environment at 170cm height during the experiments. In addition, the avatar can walk at 1,5m/s and run at 5m/s. Besides, the avatar's horizontal field of view in the simulation is 105º, while the vertical is 60º. Then, the simulation is coded to obtain coordinates and viewing directions of the participants every 0,5s through Microsoft Visual Studio.

The simulation preparations are continued in two separate branches. The first is the experiment for the regular exit group as wayfinding experiments. For this experiment, as the starting point, the avatar is placed at the deepest location on average from the exit doors of the building (Figure 2). In this wayfinding experiment, all emergency exit signs are hidden not to guide participants to find out the exit doors. In contrast, all the egress signs are visible in the emergency exit experiments. In this case, the avatar's starting point is located at another deepest place according to the egress doors. Shortly, avatars are placed at the deepest points on average to enable participants to experience the virtual building as much as possible.

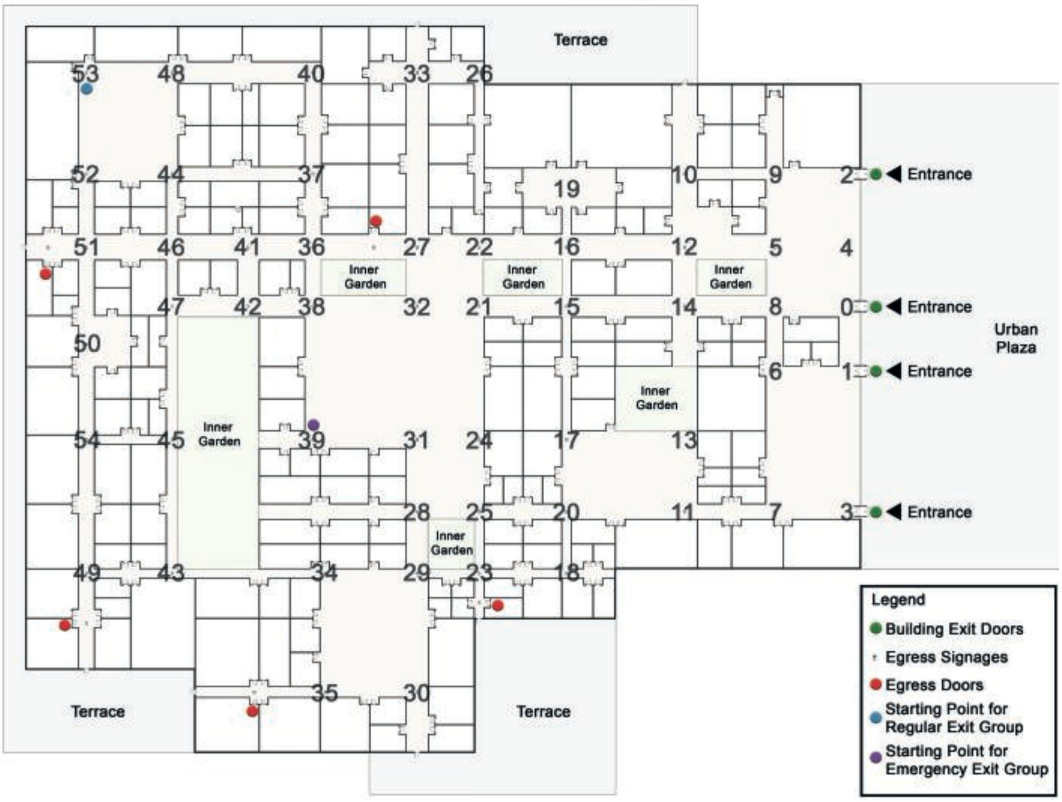


Figure 2: Nodes, Location of Exits and Starting Points for Wayfinding and Evacuation Groups

Besides, a pilot study is created to reduce the inequality in participants' computer and computer gaming experiences. Before starting the actual simulation experiment, people are motivated to wander freely for 90 seconds in order to become familiar with the experimental conditions. This pilot study is done virtually in a relatively small two-story building. This stage is also prepared with the same method as the actual simulation experiments.

Before each experiment, the participant is randomly assigned into one of the two sampling groups. Furthermore, the experimental studies are carried out with 44 people in total. These experiments are conducted over online meetings via Zoom software (Figure 3). All sessions are recorded and the virtual simulation software is sent to the participants via WhatsApp Web, Mail, or Zoom during the meetings. At the beginning of each experiment, an informative presentation is made to the participants. In this phase, these respondents' data are collected as gender, age, education level, profession, and computer gaming experience.

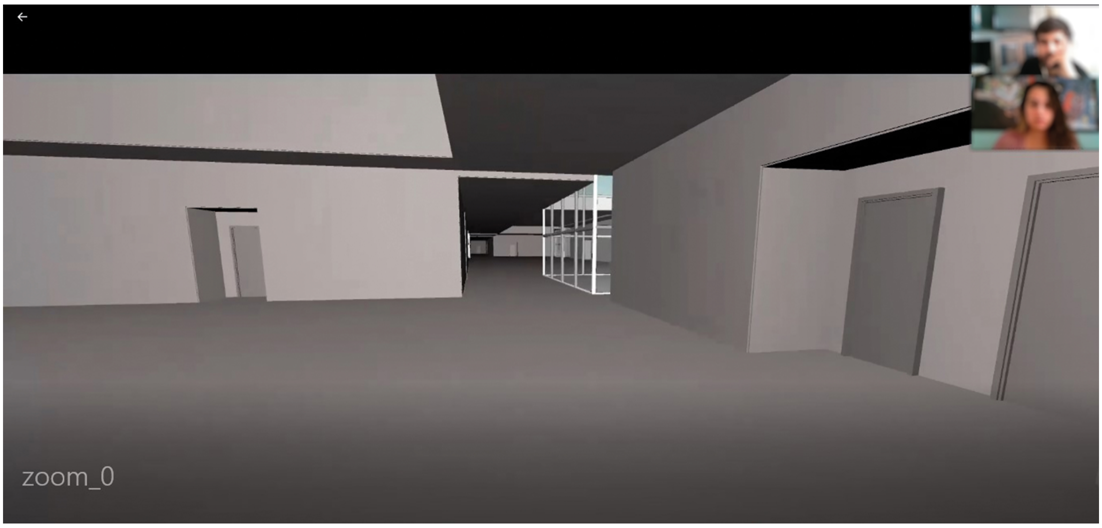


Figure 3: Simulation Experiments over Zoom

During the presentations, the first group is given the task of finding one of the regular exit doors of the building. The second sampling group is asked to evacuate the building through the egress or building exit doors as quickly as possible. Eventually, participants consecutively attended the pilot study and the actual experiment in each session. Unfortunately, the kinesthetic data values could not be obtained from the experiments of eight participants due to technical issues. These experiments are not evaluated. As a result, each sample group consisted of 18 people as nine female and nine male participants in each group. The average age of the wayfinding group is 29.94, and the average age of the evacuation group is 29.55.

Normalized time diagrams are made before obtaining the objective assessments. In these diagrams, the time spent during the experiment is divided into ten equal steps for each participant. Then, participants' routes as footsteps are overlayed and visualized separately for each phase for wayfinding and evacuation groups. These diagrams are intended to reveal the collective tendencies in spatial decision-making and to discover issues during the wayfinding and evacuation processes. In this way, this process reveals the nodes and the areas that are passed or not during the simulation experiments.

The objective assessment focused on the correlations between 2D syntactic data and kinesthetic data for exit and evacuation groups. In this context, isovist area, isovist perimeter, and drift are focused as isovist data. On the other hand, circularity, standard deviation, variance, and skewness are handled as the radial data. Moreover, depth, mean depth, and integration are examined as the graph data. 2D isovist and radial data values are calculated by the 'Isovist' component of 'DeCoding Spaces', a plug-in of the Grasshopper software. On the other hand, graph data values are obtained through a plug-in of Grasshopper software, 'Space Syntax,' and its components. Again with the same plug-in, axial integration and nodal integration diagrams are created. All these parameters are measured from the midpoints of nodes or axes. Furthermore, the frequency of interpasses, frequency of stepbacks or stops, and frequency of turns are obtained as the kinesthetic data during the analysis phase. Unlike 2D syntactic parameters, these parameters are obtained by manually counting the participants' spatial behaviors around the nodes. The relations are established with the Pearson correlations over SPSS software.

The subjective assessment concentrated on the correlations between personal data and kinesthetic data. In this case, personal data is listed as gender, age, education level, profession, and gaming experience. On the other hand, the passed distance, duration, average speed, number of stepbacks or stops, and number of turns are reviewed as kinesthetic data. Moreover, these kinesthetic data parameters are obtained the same as the objective assessment method. The correlations are revealed with the ANOVA test over SPSS software.

In this study, the creation of polyhedron form consists of two stages: scattering the rays from the observation point towards the volumetric space and covering the points with mesh surfaces where the rays intersect with obstacle surfaces (Figure 4). At this point, the radials need to be scattered as densely as possible to obtain a more accurate polyhedron form representing the actual space. As a result, the shape of this volume covers any point in the observer's 360º for the field of view. This process is obtained by algorithms that are created in Grasshopper. The polyhedron form is created by the 'ParIsoVist3D' component of the Grasshopper plug-in, Impala.

In simulation experiments, the avatar's field of view is assigned as 105º horizontally and 60º vertically in the looking direction, as mentioned before. This kind of three-dimensional field of view may be called optimized polyhedron volume. In this case, the shape of the optimized polyhedron is obtained by cutting the polyhedron form from the vantage point at angles by using Grasshopper software. In this way, the optimized polyhedron volume and the optimized polyhedron surface area values are measured. Besides, these geometrical polyhedron properties such as polyhedron volume and optimized polyhedron volume may be called polyhedron data.

Besides polyhedron data, polyhedron radial data values may also be calculated. As an alternative for the 2D circularity, the spherical circularity variable may be one of these radial data values for the volumetric visibility concept. Dalton and Dalton (2001) state that the circularity value provides an idea of how close the observation point is to the center of the visible space and provides information about the approximation of the isovist form to a circular shape. He mentions that the resulting value is obtained by dividing the multiplication of the 'π' with the average radial length by isovist area ($\pi. \bar{r}^2/A$). Accordingly, the results range from 0 to 1, and numbers close to the value of 1 indicate high circularity. Benedikt (1979) also states that this value is related to the ratio between compactness and complexity from another point of view. In this case, it may be expressed that the visual experience is persistently stable in compact spaces. On the other hand, Batty (2001) mentions that Benedikt made the circularity calculation as the square of the isovist perimeter divided by the isovist area (P^2/A). According to the formula, if the resulting value is 1, there is perfect circularity, while if it is greater than 1, it means that circularity is lower (Benedikt 1979). Although Benedikt (1979) defines circularity as isovist data, it may also be regarded as radial data according to the formula expressed by Dalton and Dalton (2001).

The discussed value as ‘spherical circularity’ is the alteration of Dalton and Dalton's (2001) circularity formula regarding the sphere volume formula in this article. In this sense, spherical circularity is calculated as the division of ‘$4/3.\pi.\ \bar{r}^3$’ for the polyhedron volume. The ‘$\bar{r}$’ variable indicates the average radial length of the polyhedron. The possible results here are between 0 and 1. The value of 1 denotes the perfect sphere. In this context, we may mention that the spherical circularity value rises when the volumetric compactness increases and the three-dimensional spatial complexity decreases. On the other hand, it may also indicate how close the vantage point is to the center of the volumetric space. Spherical circularity values might be consciously interpreted in wayfinding evaluations, especially when investigating human behavior hesitations.

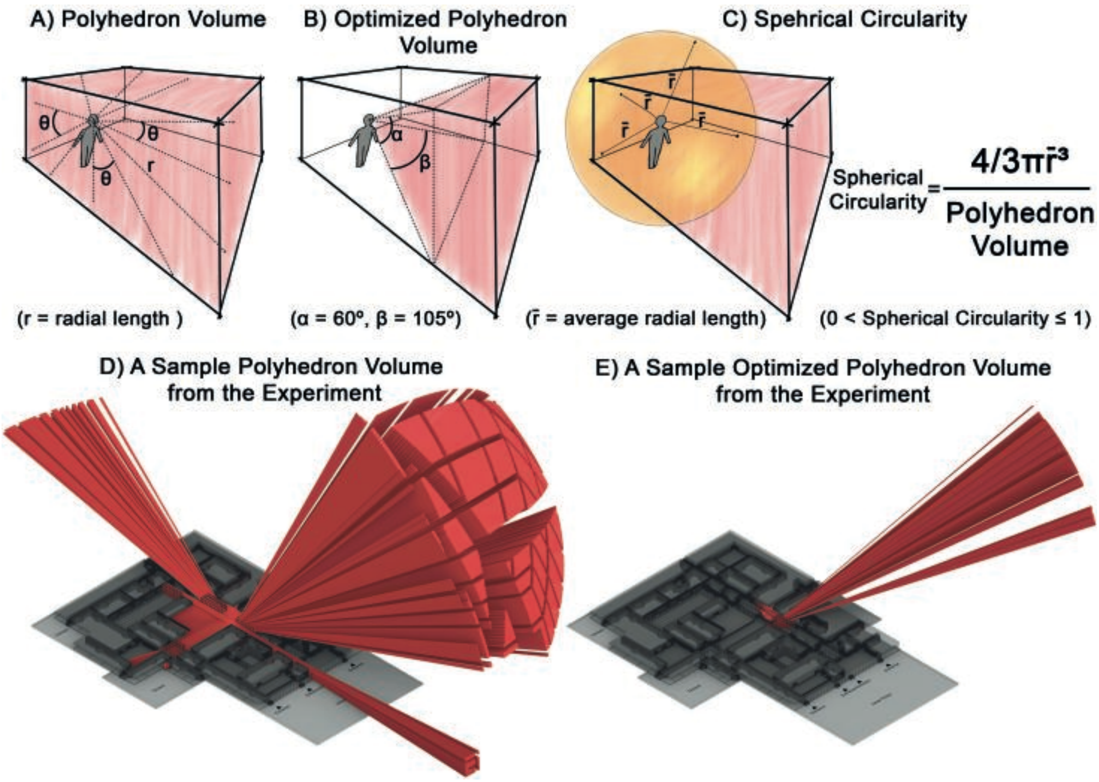


Figure 4: A) Polyhedron Volume, B) Optimized Polyhedron Volume, C) Spherical Circularity, D) A Sample Polyhedron Volume from the Experiment, E) A Sample Optimized Polyhedron Volume from the Experiment

The sequential objective assessment covered the correlations between volumetric visibility data and kinesthetic data. In this sense, average polyhedron volume, average polyhedron surface area, average optimized polyhedron volume, and average optimized polyhedron surface area are examined as polyhedron data. Besides, average spherical circularity is investigated as the polyhedron radial data. On the other hand, spent time, duration of stops, frequency of head rotations, and frequency of unmatched movement and looking direction are handled as kinesthetic data. Unlike the other two assessments, these parameters are obtained sequentially around the nodes as decision-making areas. The relations are established with the Pearson correlations over SPSS software.

The sequential computation model can be seen as a highly functional method to obtain instantaneous perceptual and behavioral data in human wayfinding. In this case, the issue of data management might be problematic. Capturing and recording every perceptual moment reveals enormous amounts of data. Bhatia et al. (2013) mention that adding a third dimension to the 2D models requires a high computer processing capacity. Grouping, analyzing, and systematically interpreting these data may also be challenging for researchers. However, algorithmic computational methods may greatly facilitate data grouping and analysis of these kinds of research.

To make sequential calculations, each decision-making point is taken with the surrounding as a square of approximately 50 sqm, and the participant's volumetric visibility data and kinesthetic data values are taken into the account for consecutive measurements when they are within these borders (Figure 5). A series of specific algorithms in Grasshopper is created to handle this process. This process is not including all points on the route, but it contains only the points inside these areas in the calculations that are reduced the computer’s processing time and avoided exceeding the CPU capacity. While considering these values, the averages are calculated for each node.

Figure 5: A Sample Route and the Decision-Making Zones in the Trajectory for Sequential Measurement

4 ANALYSIS AND RESULTS

In wayfinding experiments, eleven (%61) participants exited the building from node number 0, whereas five (%28) from 3, and one (%5,5) from node 2. On the other hand, one of the participants could not find the exit door and quit the experiment in node 12. In the evacuation experiments, ten (%55,5) respondents evacuated the building from node number 36, whereas four (%22,5) from 23, one (%5,5) from 0, one (%5,5) from 27, one (%5,5) from 35, and one (%5,5) from node 51.

Sixteen people in the wayfinding group went to the building exit doors in node 0 and node 3, which are on the axes of two of the highest axial integration values (Figure 6). Eleven of them left the building from the most shallow and most integrated exit node 0 according to the starting point of the wayfinding experiments. Although node 2 has the same depth value as node 0, only one person went to this exit. Thus, it may be argued that people tend to orient themselves to the most integrated axes during the wayfinding process, as also asserted and claimed by Peponis et al. (1990).

Eleven people in the emergency exit group evacuated the building from the egress door, which is on the most integrated axis. In this case, this most preferred door between node 36 and node 27 has the lowest depth value according to the starting point of the evacuation experiments. Furthermore, the subsequent most reached egress door in node 23 is in the second shallowest place, and this node is on the less integrated axis compared to the most preferred axis. In this case, it might be argued that people also tend to go to places that have lower depth and higher integration values in the evacuation process. On the other hand, it may also be asserted that egress signs greatly influenced the evacuation group by guiding and directing them to the closest egress doors. In this case, it should be noted that the egress signs directing people to node 36 and node 23 are in the equal distance and angle according to the starting point of the evacuation experiments. Besides, the locations of these egress signs (node 38 and node 31) have almost the same nodal integration values. It seems that most of the attendants could see the emergency exit signage guiding to node 36 at first. In this context, it would be also asked in here what syntactic parameter or parameters made this signage more visible than the other, this might be the essence of this argument.

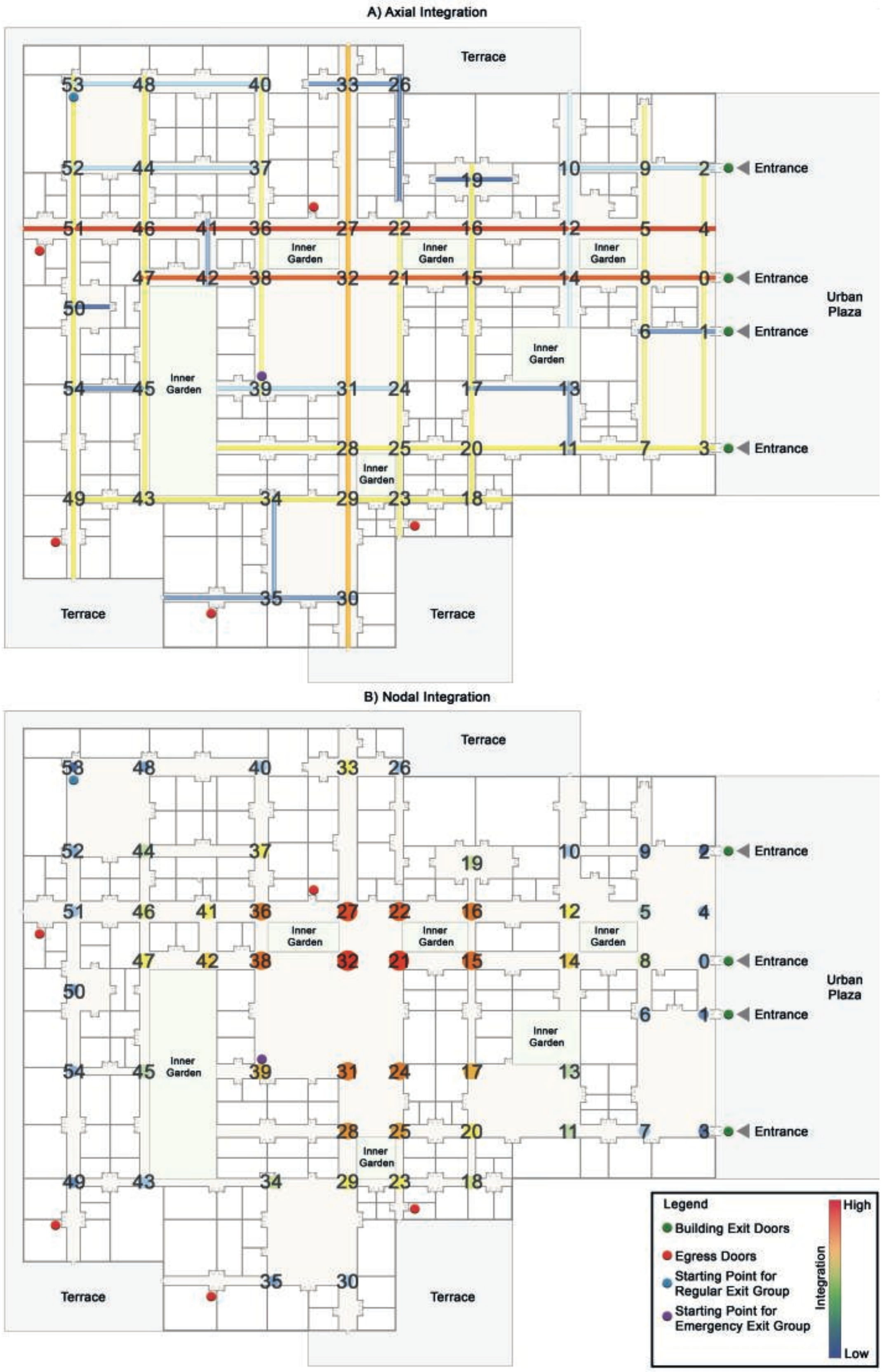


Figure 6: A) Axial Integration, B) Nodal Integration

It may be argued that people primarily tend to discover the nearby places during the wayfinding process, as shown in normalized time diagrams (Figure 7). Furthermore, participants in the wayfinding group explored the shallowest areas until the fourth step. On the other hand, people traced almost all the spaces behind the center hall until the seventh time period. Therefore, it would be argued that people spent most of their time exploring adjacent locations until they reached the center hall by also retracing the routes they had passed before. After that, they quickly headed towards the regular exit doors. In this case, it may be expressed that human movement creates the understanding of the building configuration, and each action during the exploration leads better performances in pathfinding, as stated by Haq and Zimring (2003). In addition, the building's topological complexity may have caused the tendency to explore the nearby surrounding at the beginning and by time respondents may comprehend the building by tracing the shallower places through the deeper spaces with various directional trials around the integrated axes. In this context, O'Neill (1991) puts forward that "…as topological floor plan complexity increases, people tend to experience greater difficulty not only enroute to the destination but in terms of absolute performance as measured by the amount of time it takes to reach destination." (p. 276).

Unlike wayfinding experiments, there is an obvious path revealed in the emergency exit experiments. Most people preferred to exit the building from the shallowest point between nodes 36 and 27. Since the egress signs are assigned to guide people to the closest emergency exit doors, they may be highly effective in directing participants to these doors. Participants who evacuated the building from relatively deeper egress doors expressed in the informal interviews that they did not see the signs at the beginning of the experiments, but they headed towards the emergency exits after a while when they could see the egress signs.

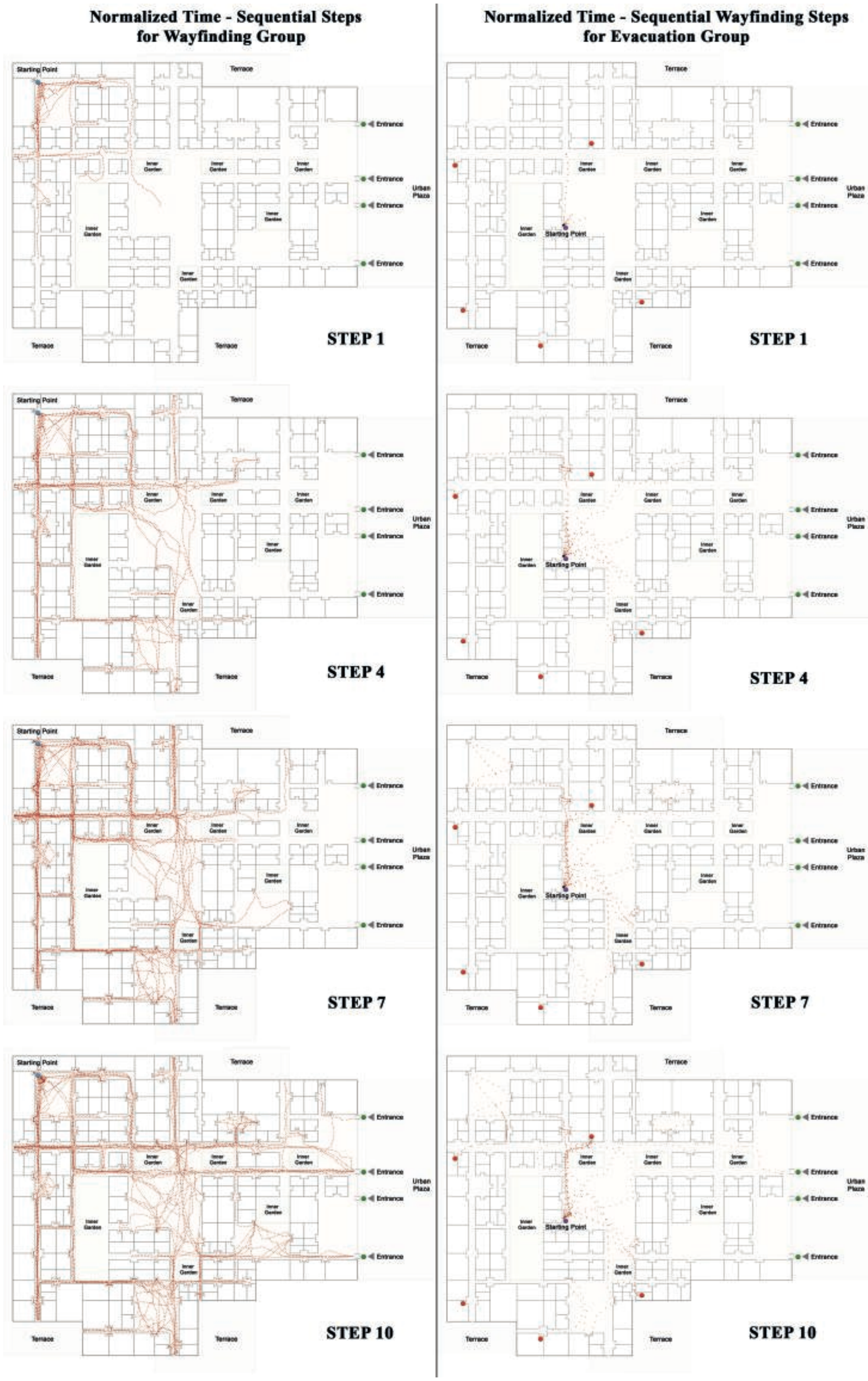


Figure 7: Normalized Time Diagrams for Wayfinding and Evacuation Groups

The correlations between 2D syntactic data and kinesthetic data are initially investigated in objective assessments. The significant results are found with isovist perimeter, drift, circularity, skewness, depth, mean depth, and integration parameters in wayfinding and evacuation issues (Figure 8). In this context, it would be appropriate to start discussing wayfinding issues with graph data, and it's one of the prevailing depth parameters.

The experiment showed that the respondents are intended to pass low depth levels more frequently (r=-,555**, p=0,00≤0,05). In this case, it would be argued that people tend to explore the places nearby themselves at first. Moreover, participants made more stepbacks or stops (r=-,485**, p=0,00≤0,05), and they did more turns (r=-,510**, p=0,00≤0,05) in the areas of presenting low depth. In this context, it would be expressed that participants show more hesitations in shallow places in which they don't have any development about the space and, in sum, spatial memory yet.

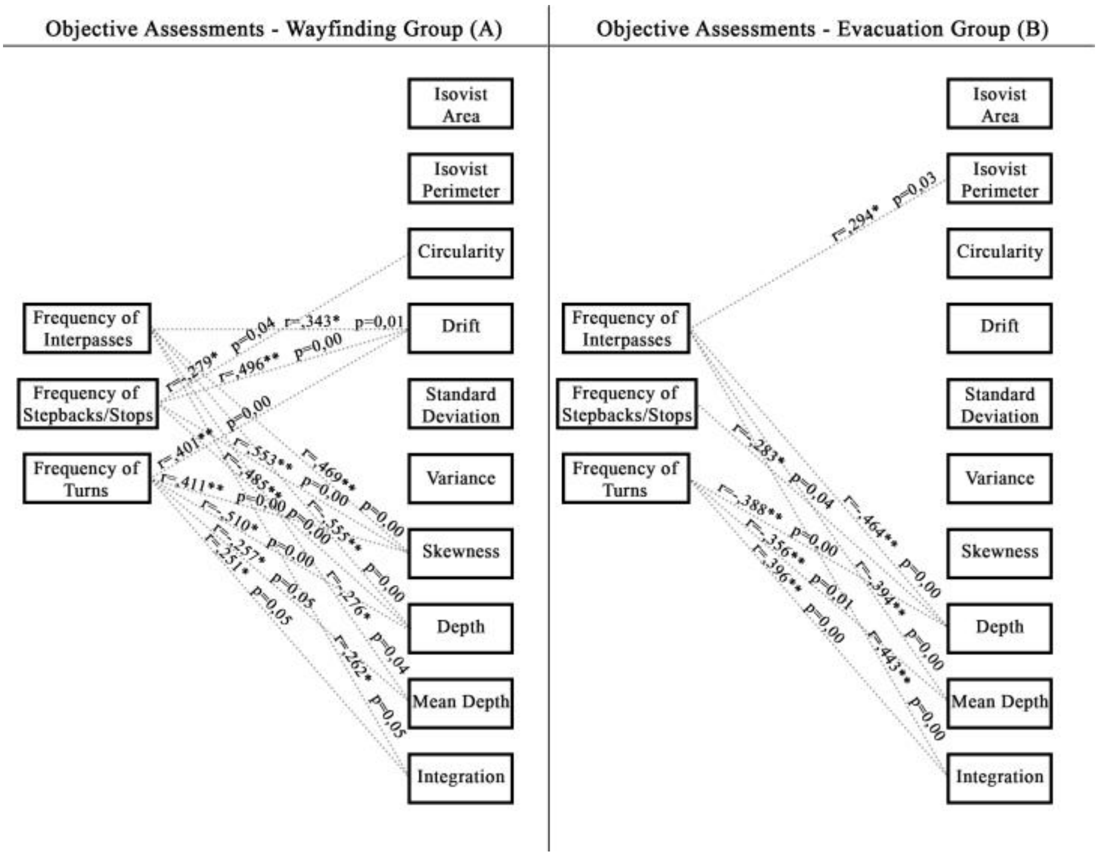


Figure 8: Objective Assessments

The depth parameter was also found significant with the evacuation group. People in the evacuation group also frequently passed shallow levels (r=-,464**, p=0,00≤0,05). On the other hand, people also made more stepbacks/stops (r=-,283*, p=0,04≤0,05) and more turns (r=-,388**, p=0,00≤0,05) in shallow places. It should be stated that most of the participants in the evacuation group exited the building from the shallow nodes according to the starting point of the emergency experiment. Therefore, the hesitations might have emerged when the participants try to understand the virtual environment and see the direction of the signs at the beginning of the experiments.

The mean depth and integration values are reversely correlated parameters with each other, so as stated before, the integration is the inversed and normalized version of mean depth. Therefore, discussing the correlations between integration and behavioral data will be sufficient. The opposite of the statements about integration will be valid for the mean depth variable.

In the wayfinding experiments, subjects more frequently passed by the nodes with high integration values (r=,262*, p=0,05≤0,05). This result might be contradictive with the results that occurred in depth variable. However, it would also indicate that people might primarily explore their nearby surroundings close to the integrated zones. Although attendants turned more in the nodes with high integration values (r=,251*, p=0,05≤0,05), there occurred no correlation between integration and frequency of stepbacks or stops. It would imply that participants are roughly developing a memory about the spatial configuration by showing less hesitation in these places that they are not fully comprehending the whole building. In this case, due to the lack of spatial memory about the virtual building, people might have tried to go in different directions and come back to the integrated zones during the spatial exploration process, as discussed by Peponis et al. (1990).

The integration parameter is also significant in the evacuation group. However, this result might be misleading. The starting point and the most preferred egress doors are in the most integrated spaces. The only argument is that egress signs may prevent people from going out of this most integrated part of the building. As a result, subjects more frequently passed (r=,443**, p=0.00≤0,05) from the most integrated zones and turned more (r=,396**, p=0.00≤0,05) in these places. Because most of the actions are happened around this most integrated part of the building, most behavioral data are inevitably revealed in this zone. However, these nodes revealed no correlation between the frequency of stepbacks or stops and integration variables. This situation also supports the argument that signage might be highly influential in guiding participants to the exits.

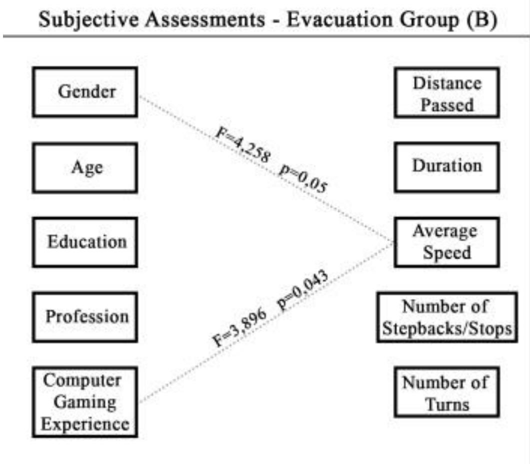
If we continue with isovist data, it is revealed that isovist perimeter and kinesthetic data have correlated significantly in the evacuation experiments. The isovist perimeter indicates the metric measure of visible borders of the environment. As a result, participants more frequently passed from the nodes with high isovist perimeter values (r=,294*, p=0,03≤0,05). The starting location of the emergency exit group is in one of the largest halls containing transparent surfaces with window frames and many respondents completed the experiment around this area. These window frames dispersed the isovist form, and therefore, the high isovist perimeter values inevitably correlated with the frequency of interpasses variable.

The drift parameter is also a significant variable for the wayfinding group. People more frequently passed from the nodes with the high drift values (r=,343*, p=0,01≤0,05). In this case, locations with high drift values may be conceived as points far from the center of an observer's field of view. Because the building exits should be at the intersection points between indoor and outdoor areas, people may have looked for these exit points by often passing through nodes far from the center of their field of view. On the other hand, people made more stepbacks or stops (r=,496**, p=0,00≤0,05) and more turns (r=,401**, p=0,00≤0,05) in spaces with high drift values. In this case, the locations with high drift values may offer human beings a high amount of visible data and various directions to go. Thus, people may be aimed to increase the opportunity for perceiving around for a while during the wayfinding.

The circularity variable is one of the radial data that is significantly correlated with kinesthetic data in the wayfinding group. It was revealed that people more frequently made stepbacks or stops (r=,-279*, p=0.04≤0,05) in the nodes with low circularity values. The value of circularity gives an idea of the 2D compactness or complexity of the space. In this sense, participants may have tended to show hesitations by making more stepbacks or stops in places over higher complexity valued nodes. These spaces may have significant linearity in multiple directions and visual inconsistency. Therefore, these places may confuse people and entail hesitations about which direction to navigate. It may be stated that, besides topological complexity, the two-dimensional visual complexity might also entail difficulties in wayfinding.

The skewness parameter is another radial data that is significant in wayfinding experiments. People more frequently passed from the decision-making points with high skewness values (r=,469**, p=0,00≤0,05). Skewness may be described as asymmetry of the dispersion in the isovist polygon. In this context, positive skewness values indicate that short radials are more than longer ones. Accordingly, it may mean that people tended to orient to the peripheries of the building borders at first, as stated before. In addition, respondents made more stepbacks or stops (r=,553**, p=0,00≤0,05) and more turns (r=,411**, p=0,00≤0,05) in the places with high skewness values. People may have hesitated and prolonged the decision-making process to determine which direction to go in these nodes. Because once they decide to take action, they must walk long distances.

When we come to subjective assessments, the correlations between personal data and kinesthetic data are evaluated. Only two of the personal data are significant (Figure 9). These are the gender (F=4,258, p=0,05≤0,05) and gaming experiences (F=3,896, p=0,043≤0,05) of the participants who attended the evacuation experiments. On the other hand, the averages were are also considered within this scope. It was revealed that the men seemed to be more faster than women when they intend to evacuate the building. Furthermore, kinesthetically, men can turn less and they may make fewer stepbacks than women. This notion also emphasizes that men may hesitate less in evacuation compared to women. On the other hand, participants who had computer gaming experience are also faster in evacuating the building. They also made fewer stepbacks. This case would indicate that people with high computer gaming experience could control the avatar easier than others.



Averages - Evacuation Group (B)

		Distance Passed (m)	Duration (s)	Average Speed (m/s)	Number of Stepbacks	Number of Turns
Gender Averages	Woman (9)	93,36	45,66	2,60	0,88	2,66
	Man (9)	57,62	17,11	3,56	0,22	1,66
Computer Gaming Experience Averages	Yes (12)	75,66	22,66	3,49	0,25	2,25
	Low (3)	41,98	23	1,88	0,66	1
	No (3)	108,32	74,66	2,66	1,66	3

Figure 9: Subjective Assessments

After investigating objective and subjective assessments, sequential objective assessments are handled, and these evaluations revealed significant correlations (Figure 10). These parameters are correlated with kinesthetic data that are the averages of polyhedron volume, polyhedron surface area, visible polyhedron volume, visible polyhedron surface area, and spherical circularity. In these assessments, the volumetric visibility and kinesthetic data are sequentially calculated within the borders of decision-making points through a series of computer-aided algorithms.

In the wayfinding experiments, attendants spent more time (r=,492**, p=0,00≤0,05), made more stops (r=,387*, p=0.05≤0,05), and they did more head rotations (r=,572**, p=0,00≤0,05) in nodes with high spherical circularity values. Furthermore, participants' movement and looking directions are not frequently matched (r=,498**, p=0,00≤0,05) in the nodes with high spherical circularity values. The results may be conceived as contradictive to the 2D circularity results. This inconsistency might have been caused by the height and volume factors added into the planar isovist concept or the sequential calculation method itself. In this context, the second option may be more possible to argue for the wayfinding experiments.

It should be stated that most of the participants in the wayfinding group spent much more time exiting the building compared to the evacuation group. While the average duration in completing the experiments was approximately 6:30 minutes for the regular exit group, it was 30 seconds in the evacuation group. Therefore, people in the wayfinding group might have been exhausted while searching for the regular exit doors, so that they tried leaving the building from some of the room doors, which they might have hoped them as building exit doors.

Most participants showed hesitations intensely when trying to leave the building from regular room doors. Moreover, some of these doors are nearby the decision-making points' boundaries, and, thus, the algorithm inevitably captured the revealed kinesthetic data around these zones. Accordingly, the zones where these doors are located might have high spherical circularity values, and the results might have been altered in these circumstances. Therefore, we think the correlations between volumetric visibility and kinesthetic data may be misleading. Still, it can be argued that algorithmic measurement methods capture the behavioral data more precisely than the manual counting method because some human behaviors such as degree of the head rotations and unmatched movement/looking directions remain pretty obscure. Shortly, the computer algorithm or the experiment should be adjusted to avoid capturing these types of misleading data.

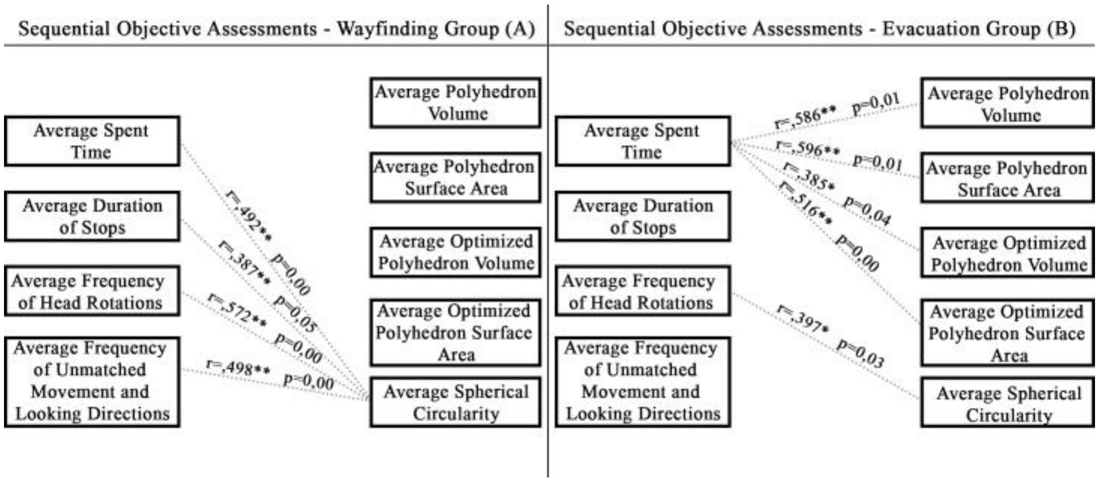


Figure 10: Sequential Objective Assessments

On the other hand, we might have captured consistent results from the evacuation experiments. It would be expressed that participants in the emergency exit group spent more time in the areas with high average polyhedron volume (r=,586**, p=0,01≤0,05), polyhedron surface area (r=,596**, p=0,01≤0,05), optimized polyhedron volume (r=,385*, p=0,04≤0,05), and optimized polyhedron surface area values (r=,516**, p=0,00≤0,05). On the other hand, these people rotated their heads more frequently in the zones with high spherical circularity values (r=,397*, p=0,03≤0,05). As mentioned earlier, these results may answer what syntactic parameters made signages more visible than others. At the beginning of the evacuation experiments, the zone with a higher volume and polyhedron surface area may have attracted people's attention. People may need to focus more deeply to perceive, comprehend, and evaluate these kinds of spaces in their surroundings. Therefore, the signage in these zones may have been perceived first, and they might guide people to the closest egress door.

In evacuation experiment, the correlation between the average frequency of head rotations and average spherical circularity may have coincidentally occurred because the participants are supposed to turn from the node with this high spherical circularity value to reach the egress door. Moreover, there were no correlations between average spherical circularity and average duration of stops or the average frequency of unmatched movement and looking directions. Hence, this situation may be interpreted so that people showed almost no hesitation in these decision-making areas. Accordingly, we can express that signages are highly effective in the evacuation processes, which may also be conceived as a wayfinding process in a sense. Finally, it can be argued that symbols may reduce the effects of spatial syntactic parameters on human perception, as mentioned by Natapov and Gewirtzman (2016).

5 CONCLUSIONS

This paper mainly focused on the correlations between volumetric visibility data and kinesthetic data in wayfinding and evacuation processes within the scope of the sequential measurement method. Besides, the 2D syntactic data are also included in this investigation. In this case, 2D syntactic data is obtained from the midpoints of the nodes, and behavioral data is collected by counting the kinesthetic movements around these nodes. In this framework, this study revealed significant 2D and 3D syntactic results related to wayfinding and evacuation issues. It may be argued that the results are consistent with previous investigations conducted by Peponis et al. (1990), O'Neill (1991), Haq and Zimring (2003), Mavridou et al. (2009), and Natapov and Gewirtzman (2016).

Besides the objective assessments, the research also focused on subjective assessments. Here, personal data values are compared with kinesthetic data values, and significant findings are found. In this context, this study is carried out with an experimental method in a virtual simulation environment. One of the highlightings of these experiments is that the experiments are done in an online platform. At this stage, the simulated environment is projected through the computer screen. In future studies, conducting experiments with VR glasses will be an essential issue for the respondents to perceive the spaces better so that we may better understand their spatial behavior.

The depth and integration parameters seem to be the primarily important factors in wayfinding processes when there are no signages. Nevertheless, volumetric visibility data becomes one of the essential parameter when the signboards are allocated in the surrounding, especially in emergency conditions. In this case, it would be argued that people tended to pay attention to spaces that have high polyhedron volumes and polyhedron surface areas. Accordingly, it is also revealed that people move forward to the directions where the optimized polyhedron volume and the optimized polyhedron surface area values are comparatively higher, especially in the evacuation experiment.

The point to be emphasized in this study is that sequential computations are made within the specific boundaries of the nodes. In this context, further studies may not be limited to the borders of decision-making zones but all the revealed data during the experiments. In this way, the correlations between syntactic data and kinesthetic data might be revealed more profoundly, especially about the issues such as human perception and spatial decision-making in evacuation or wayfinding processes.

In conclusion, this study has revealed significant results related to wayfinding and evacuation issues in complex buildings. One of them can be expressed as that the signs almost eliminate the negative effects of spatial features on wayfinding. Besides, the research has taken the concept of 3D isovist as polyhedrons and it also intended to present the results of environment-behavior issues sequentially. Today, with the developing computer technologies, vast amounts of data can be computed very quickly. Consequently, with the algorithm-based sequential computation methods and online experiments, researchers may reach the spatial and behavioral information regarding wayfinding and evacuation issues in a short time even though there is a great distance between the researcher and participants.

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