How do atria affect navigation in multi-level museum environments?

DOI: 10.1080/00038628.2021.1911782

Corresponding author

Athina Lazaridou

The Bartlett School of Architecture, UCL, London, UK

athina.lazaridou@gmail.com

Co-author

Sophia Psarra

The Bartlett School of Architecture, UCL, London, UK

s.psarra@ucl.ac.uk

How do atria affect navigation in multi-level museum environments?

How do people explore multiplex environments? What role do atria play in spatial navigation? These are critical questions for architectural design. However, few studies have examined the role atria play in visitors' exploration of museums. Consequently, the relationship between free exploration and the design of atria in museums is not well understood. A pilot study in the Ashmolean Museum indicated that atria influence navigation. The Museum, therefore, lends itself as a case study to assess the impact of visual connections upon exploration and orientation. We present an experimental study with two conditions: a highly-detailed realistic virtual model of the building and a modified virtual model of the same building, eliminating the views crossing through the atria. Two hypotheses are tested: first, that visitors' paths will be different depending on the amount of visual information they receive inside each experimental condition; second, that visitors' ease of exploring and viewing the environment will also differ. Analysis confirmed that participants followed different paths in the two experimental conditions. Users visiting the exact model turned their heads around fewer times than users visiting the modified model. These findings suggest that atria play a significant role in nudging movement and affect the ease of navigation.

Keywords: architecture; museums; spatial navigation; head movement; virtual reality

Introduction

How do people navigate inside real and virtual atria buildings? A key issue in designing complex interior spaces is the facilitation of movement and circulation. Architects use atria as aesthetic architectural elements to enhance spatial journeys and social interactions (Saxon 1993). As Werner and Long state, an atrium can act as an orientation point within a complex layout (2003). Voids offer numerous possibilities for social co-awareness due to the views crossing through them (Choi 1997). In other words, atria provide the potential for visitors to grasp the spatial relationships between the parts of the whole.

Studying the Museum of Scotland, Psarra and Grajewski (2000) argued that the three-dimensional connections established by the voids structure the relationship between architecture, the viewer and the educational message guiding visitors in their exploration of the building. In his analysis of the High Museum of Art in Atlanta, Peponis (1993) suggested that the layout provides a rich social experience, driving movement to the main atrium and creating a system of visibility in which visitors structure the foreground, while at other times forming the background. It seems that the interplay between local and global visual cues offered in two and three-dimensions inside museums have the potential to enhance spatial experience.

According to Frankenstein et al. (2012), a spatial attribute that can additionally influence navigation is the landmarks situated inside complex buildings. Their study showed that people use landmarks to gather information related to their target. Further, Denis et al. (2007) stated that landmarks assist people in finding their way around, allowing them to avoid mistakes. The artworks positioned inside atria could further serve as markers guiding and influencing human exploration.

Current research is mostly based on the reasonable hypothesis that atria carry a cognitive function as reference points, enhancing spatial exploration and social co-awareness. However, a systematic study regarding the ways in which atria and three-dimensional connections among spaces influence navigation is generally lacking. This research aims to clarify the relationship between the three-dimensional composition of space and movement.

Background

Exploration and wayfinding

Spatial navigation research concerns the type of navigation tested, the setting within which the testing is carried out, and the spatial features affecting movement. Type of navigation can be differentiated between wayfinding (a path to a particular destination) and spatial exploration (what is available and interesting in an environment) (Peponis 2016). Another definition of spatial exploration, given by Wiener et al. (2009), is the behaviour characterising undirected wayfinding, which is a wayfinding process without a specific destination.

However, as wayfinding research asks participants to reach a particular location, it can potentially bias people towards meeting their goal, independently of features designed to guide their unconstrained experience such as atria. It is thus limited in its capacity to capture the role such features play in how visitors freely move within a layout.

Horizontal and vertical wayfinding

Research on wayfinding inside complex buildings typically explores two-dimensional layouts as isolated floors (Montello and Pick 1993; Hölscher et al. 2009). A study by Natapov et al. (2019) investigated two-dimensional building circulation types in relation to wayfinding by conducting a spatial analysis of layout visibility, based on participants' subjective evaluations. However, by eliminating the vertical elements of the building in order to simplify the plan, the study altered the actual three-dimensional architectural experience.

There are, however, various studies that have explored wayfinding in multi-level buildings. One of them is Kuliga's (2016) attempt to evaluate wayfinding, using peoples' subjective experiences in multi-level buildings with the goal of making the layouts more user-friendly. Another is by Lu and Ye (2017), who investigated whether multi-level buildings are memorised as volumetric maps or collections of floors. Their work indicated that people remember a complex layout as a volumetric map, highlighting the importance of three-dimensionality. Hölscher et al. (2006) studied how experienced and inexperienced participants navigated inside a multi-level conference centre. Behavioural differences were identified between the two groups, who reported wayfinding problems due to the lack of visual access to vertical points of circulation and incongruent floor layouts. In their later examination of wayfinding strategies in complex buildings, Hölscher et al. (2009) showed that users first move horizontally towards the target area, thereafter changing floor to reach their goal.

Further, Brandt et al. (2015) conducted an experiment inside a multi-level hospital that required participants to point towards invisible goals from their position. They found that the participants' understanding of the building was distorted: it was both taller and horizontally smaller than they perceived it to be. The researchers related this finding to the behavioural performance of horizontal and vertical navigation in multi-level buildings. As Brandt et al. (2016) argued, orientation and navigation in three-dimensional layouts is more complex than in two-dimensional ones.

The above studies employed human participants, while Gath-Morad et al.'s (2020) research presented a computational framework (cogARCH) using agents to evaluate their wayfinding performance in multi-level buildings. However, the agents did not illustrate wayfinding variations when the architecture was modified and neither were the results cross-referenced with empirical findings.

Head movement, gaze direction and route choices

A critical issue related to navigation is how people scan the environment in order to make route choices (e.g. Haq and Zimring 2003). The relationship between head movement, the direction of gaze and the decisions people perform when moving are of central importance in studying spatial navigation. Specifically, head movement in VR was found to determine participants' gaze direction (Christou et al. 2016). The field of view in the VR system was 110°, the same as that in the Oculus Rift. Results showed that head movements were crucial, because users had to maintain awareness of their position along the path while evaluating their position in relation to the upcoming junctions (ibid.). A study by Bowman et al. (2004) indicated that the large field of view (110°) in VR reduced the amount of head movement allowing users to understand spatial relationships more easily. Similarly, Barton et al. (2014) proved that the frequency of visitors' head turns is higher during a navigation task with a limited angle of vision. It seems that studying head movement in VR can bring up valuable results regarding exploration. The present study focuses on head movement in VR, aiming to understand how the volumetric treatment of buildings, which is often purposely designed to aid navigation, impacts on exploration.

Measurement techniques for visual information

Architecture can affect navigation through the composition of vistas enabled by atria, openings in walls and transparent materials. Various techniques have emerged over the years mapping visual spatial information. First, Benedikt (1979) developed the "isovist" tool. An isovist is "the set of all points visible from a given vantage point in space" (ibid., p. 47). However, isovists reduce a 3D world into a two-dimensional representation. The notion of the isovist was later extended by Morello and Ratti (2009), who created a three-dimensional urban composition of buildings which focused on visibility across buildings, although their method was not supported by empirical findings. Recently, the "Nebula" software was used to analyse isovists' point clouds in a university and showed that 3D isovists, centred on a display, improved users' recall of display content over 2D isovists (Dalton et al. 2015). However, the display was located in a single-storey environment and not in a multi-level layout, limiting the three-dimensional exploration to two-dimensional visual relationships.

Research using space syntax employs analytical diagrams graphing visual relations in two dimensions. Space syntax is a series of theories and techniques that quantify spatial characteristics in relation to patterns of human activity and movement (Hillier and Hanson, 1984). One of the techniques is Visibility Graph Analysis (VGA) which produces a graph of inter-visibility relations of spatial locations in a grid superimposed on a building plan (Turner et al. 2001). Based on VGA, a multi-directional graph representation was proposed by Varoudis and Psarra (2014), using a combination of 'directed' and 'undirected' visual relationships to describe three-dimensional space. However, this analysis lacked empirical testing regarding how people use visual information through atria to navigate inside multi storey buildings. Due to the insufficient cross-evaluation of the above 3D techniques with real-time data, the present research uses VR technology to examine how movement is configured in volumetric environments.

Virtual reality as a means to explore spatial navigation

The study of spatial exploration in real world environments presents methodological limitations, due to its complexity and the lack of control over them (Kimura et al. 2017). VR is used to achieve controlled experimental conditions to explore human navigation. It allows for systematic manipulations that cannot be implemented in occupied real environments. Also, it can help examine the validity of architectural proposals and design alternatives aiding the design process (Portman et al. 2015). VR offers the possibility of simulating complex settings by providing the basis upon which architectural and psychological studies can take place (Kuliga et al. 2015). For example, by intervening in their design of galleries in VR, Lu & Peponis (2013) showed that exhibition visitors are sensitive to patterns of display co-visibility in galleries.

The reliability of VR has been tested by Bishop & Rohrman (2003), Haq et al. (2005) and Franz & Wiener (2008). They showed that virtual environments offer a reliable methodology to capture real-world behaviours. A limitation of virtual environments is that they cannot represent the exact ambience of the real world. Video games might overcome this limitation, as they can provide a high degree of correspondence with the real world. A video game was used to compare how people navigate in a digital world compared to the real cities of London and Paris (Coutrot et al. 2019). Findings in the two cities were very similar, while the use of video games did not alter the results. Further, when the virtual wayfinding task became more difficult, the strength of the correlation between real world and virtual environment increased too. Research on navigation could benefit from video game investigations; however, not many studies have used video games comparatively with empirical data to check the validity of the results.

In our study, we use VR technology, which allows for the comparative testing of the exact virtual model of a building with a modified model of the same setting. The present study focuses on two hypotheses: a. whether the elimination of views through the atria affects visitors' paths and gaze direction, with all other aspects of spatial organization remaining unchanged; b. whether the manner in which visitors views the museum and navigates also differs.

Methodology

Case study: The Ashmolean Museum

The Ashmolean Museum in Oxford, UK, was designed by Charles Robert Cockerell (1845) and has undergone a succession of additions, most recently by Rick Mather Architects (2009) (Figures 1, 2). The architects inserted four atria (A, B, C, D) of different size and shape to bring light to the rear of the layout. The mix of double-height and single-height galleries, glazed surfaces, as well as the staircases and bridges that traverse the double-height spaces, provide three-dimensional vistas connecting galleries with each other (Figure 1).

The Museum's composition is formed by three main axes. The first axis, named as 'left-to-right', links the entrance with the Egyptian collections on the western side of the building. The second, referred to as the 'front-to-back' axis, connects the entrance with Atrium A; and the third is the ´western' axis, running parallel to the front-to-back axis, linking the galleries located on the west side of the museum with atrium C at the far end of the building.

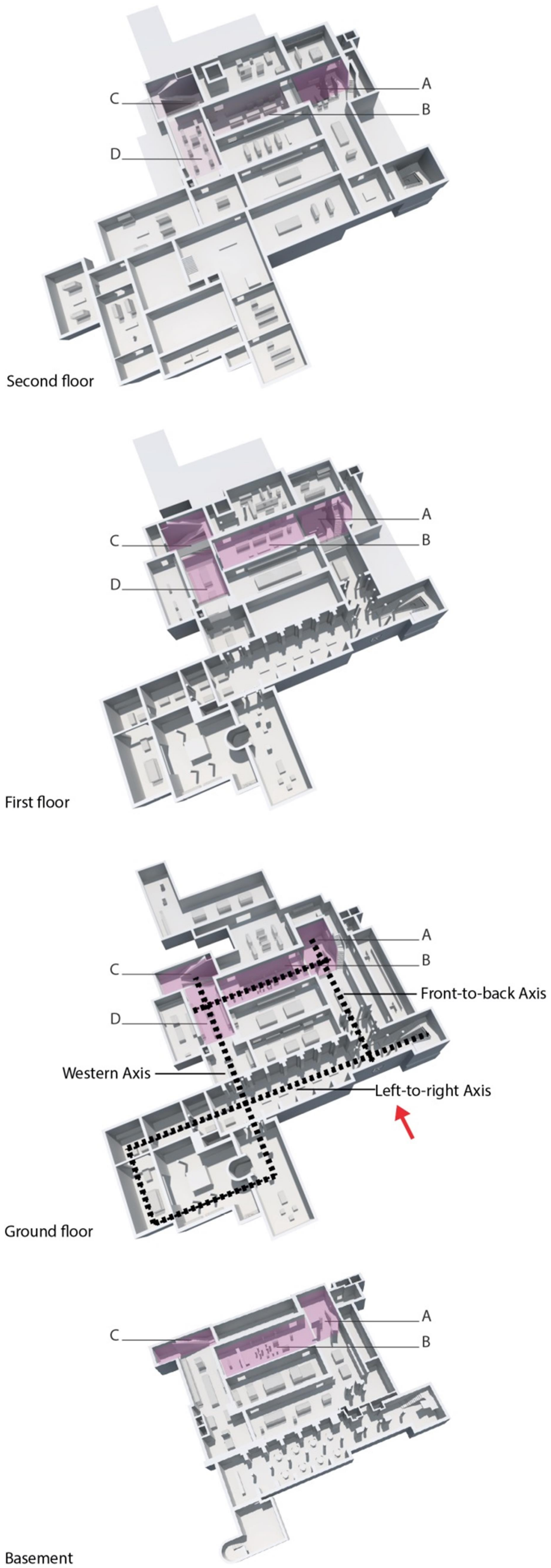


Figure 1. Exploded axonometric views of each floor plan of the Ashmolean Museum.

Pilot study in the real museum

We previously conducted a pilot study using detailed tracking of visitors' paths in the real Museum, in order to investigate how people explore the building and how atria influence their navigation (Lazaridou & Psarra 2015). Two hundred participants were observed in total, on the four floors of the real Ashmolean (50 visitors per floor). They were randomly selected upon entering every floor and tracked for a maximum of one hour each until they changed level, after which the researcher moved to observing the next participant. The tracking started from the entrance of the Museum on the ground floor, and the staircases that were close to atria A and C. Sixty-one percent (61%) of visitors were male and 39% female. Thirty-two percent (32%) were between 18-30 years old, 14% were between 30-45, 24% between 45-60 and 30% were 60-75 years old.

Visitors' paths through the real building were mapped in a detailed manner on physical plans by the researcher and afterwards digitised using Autocad 18, Adobe Illustrator CS6, and analysed with QGIS. The paths on different floor layouts were compared using convex maps as developed by space syntax (Hillier & Hanson 1984). A convex map consists of the least set of fattest spaces covering a two-dimensional plan, with all pairs of points being intervisible (ibid.).

Following the pilot study, we moved on to create two different models of the Ashmolean for VR experiments: a. an exact model, representing the museum in its realistic condition; b. a modified model, where the atria are closed off, by replacing the glazed facades surrounding the voids with opaque materials. The use of non-transparent materials in the second scenario obstructs visitors' visibility through the atria towards the same and the adjacent floors. Visitors' paths in the real building were subsequently compared with movement patterns in the virtual models. The results of the real study, the VR study and their comparison are discussed in the following sections.

The exact three-dimensional virtual model and the modified three-dimensional virtual model

The exact model of the museum was created as follows: first, a detailed model was drawn in Archicad 19. Optimised three-dimensional mesh-representations of exhibits were subsequently imported into the model and placed in their exact locations. These were derived from 5,000 panoramic photographs taken in the actual building and processed using Autodesk's Memento Beta software (https://memento.autodesk.com/about) (Figure 2). Acoustic conditions were simulated using a compilation of real sounds recorded in the Ashmolean by the researcher. These sound recordings were from people walking, talking and included background noises. The only significant difference between the virtual and the actual museum environment was the absence of people in the virtual setting (Figure 2).

The three-dimensional model was imported in Unity 5.1.2f1 to eliminate the possibility of moving through virtual walls and to set up the virtual visitor (First Person Controller) whose height, eye elevation and walking speed were set at 1.67m, 1.60m and 1.79m/s respectively. The walking speed was tested during a preliminary study with 10 participants to evaluate whether they could navigate the whole building within the time limit (15 min) of the experiment. 15 minutes was set as the maximum time due to the motion sickness experienced by some participants in the pilot study. No acceleration was allowed.

The exact three-dimensional virtual model was next modified to create the second experimental environment (modified model) (Figure 3). In this model, the glazed walls, balustrades and openings surrounding the atria were replaced with opaque walls.

Figure 2. Views of the real (left) and the virtual environment (right).

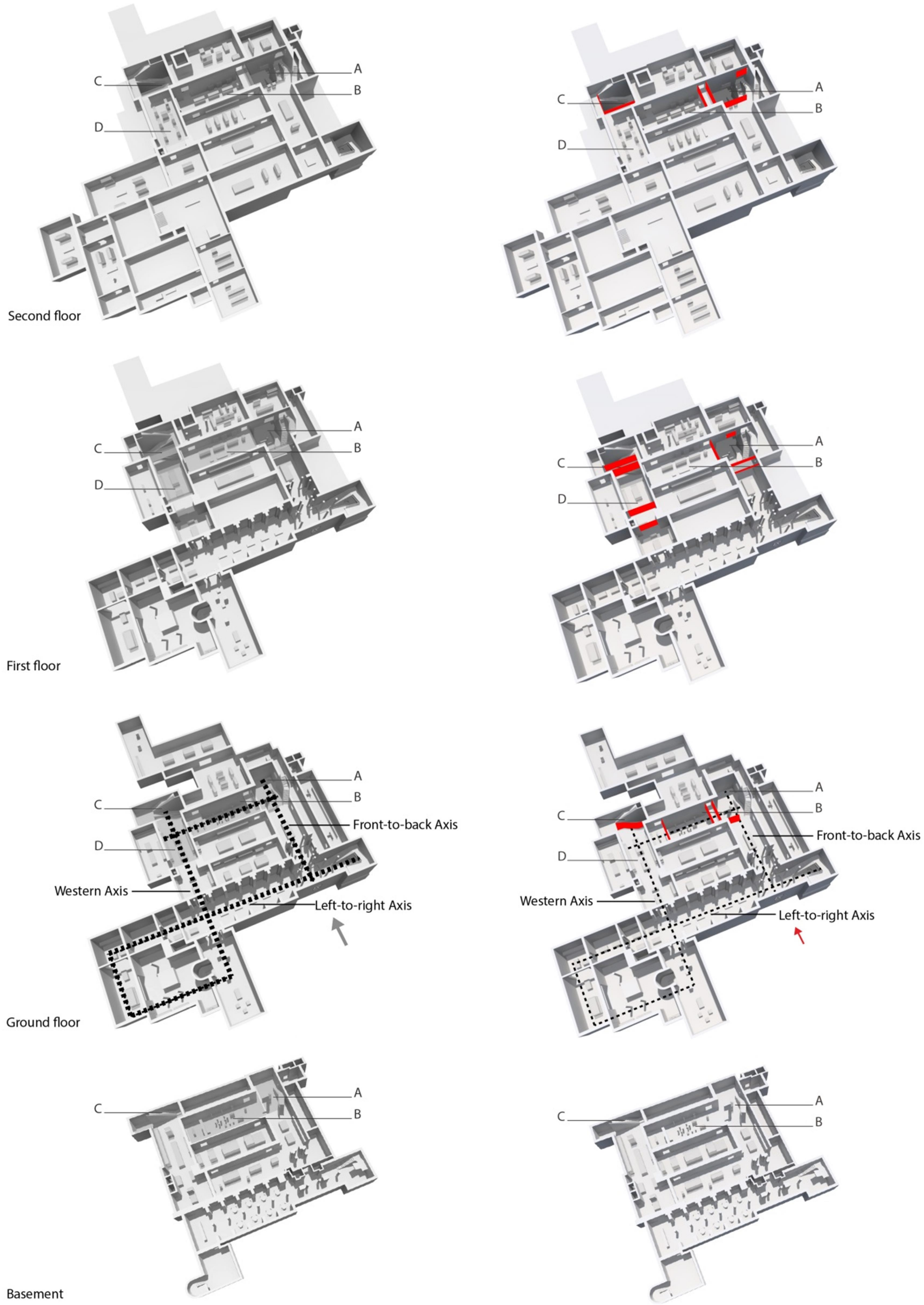


Figure 3. Exploded axonometric views of each floor plan of the exact model (left) and the modified model (right). The changes are highlighted in red.

The VR experiment

The study has been approved by UCL with an Ethics Project ID Number: 6317/001 and a Data Protection Registration Number (Z6364106/2014/11/39). Each participant completed an informed consent letter and a participation form. Before and after the experiment a questionnaire was administered regarding participants' demographic data, the VR technology and the experience it offers in conducting the experiment. The results of the questionnaire are presented in the next section.

Before starting the actual experiment for the Ashmolean, an additional pilot study with 20 participants was conducted using a virtual model of the Museum of Scotland, Edinburgh, to test the operational familiarity of participants with virtual movement and to avoid any bias related to prior experience of the virtual Ashmolean Museum. Those users that encountered difficulties in handling the equipment were excluded from the experiments.

The experiment ran on an iMac with an operating system OS X Yosemite, Windows 7, 21.5', LCD, Core 2 Duo, 4GB RAM, based in the Bartlett School of Architecture, UCL. The Oculus Rift Development Kit 2 Virtual Headset (DK2) was used for the experiments with a predetermined 110° field of view, an angle that was selected based on existing studies we reviewed in the paper (Bowman et al. 2004). The headset has a precise in-built positional tracking system which can track users' head movements. The paths were recorded ten times per second.

Participants were asked to freely explore the Ashmolean Museum (Figure 4). They had to visit as many spaces as possible and return to their starting point when they thought they had explored the whole building. All users were positioned at the entrance of the building facing towards the exterior, to avoid creating any bias regarding their initial route choices.

Figure 4. Views from the participants who explore the virtual models.

The participants of the VR experiments

Fifty unpaid users were recruited via an electronic invitation. Twenty-five of them navigated in the exact model and twenty-five different participants in the modified model. The users of the VR experiments were different from the people tracked in the real Museum. In order to avoid any bias due to memory effects and familiarity with the layout, the VR participants had not previously visited the Ashmolean. They were not informed which building they would navigate, neither were they given 2D maps nor explanations about the building and the collections. Table 1 summarises the participants' demographic data.

After completing the virtual experiment, just over half of the users (56%) claimed that use of the VR was easy, while 30% stated it was very easy. Seventy-eight percent (78%) experienced motion sickness, which affected their navigation endurance. However, all users finished the experiment before exiting the virtual models. Further, sixty-four percent (64%) of the participants replied in the questionnaire that the integration of sound helped them be more aware and present regarding their virtual movement.

A script logged the virtual movement from the entrance of the Museum to the end of the exploration. The script logged the movement data ten times per second in a CSV format file. The three-dimensional coordinates of the paths were recorded (x y z).

Three additional coordinates (vx vy vz) were documented indicating the turning of participants' heads in relation to the x y z axes respectively.

The next section compares navigation patterns both in the real building and in the virtual models, focusing on the effect of three-dimensionality on movement.

Exact model

Sex	52% Male	48% Female		
Age	45% _ 18-29yrs	38%_ 30-34 yrs	17% _ >40yrs	
Disciplines	36% Architects	27% Humanities	22% IT specialists	15% Researchers
Right-handed	92% Right-handed	8% Left-handed		
Vision	66% No problems			
Familiarity with VR	56% No familiarity	42% Limited experience	2% Regular interaction	
Modified model				
Sex	60% Male	40% Female		
Age	41% _ 18-29yrs	33%_ 30-34 yrs	26% _ >40yrs	
Disciplines	25% Architects	23% Humanities	17% Economics	35% Researchers
Right/Left-handed	73% Right-handed	27% Left-handed		
Vision	82% No problems			
Familiarity with VR	64% No familiarity	32% Limited experience	4% Regular interaction	

Table 1. Demographic data of the participants who participated in the VR experiments.

Results

Navigation in the real Ashmolean

The analysis of movement in the real building reveals two kinds of exploration patterns, indicated as 'a' and 'b' (Figures 5, 6). Exploration pattern 'a' refers to the 48% of visitors who on entering the building follow the front-to-back axis towards Atria A and B. Exploration pattern 'b' concerns the other 50% of visitors who choose the left-to-right axis, moving along the sequentially arranged galleries on the left side of the building. The remaining 2% turn right and move to the basement.

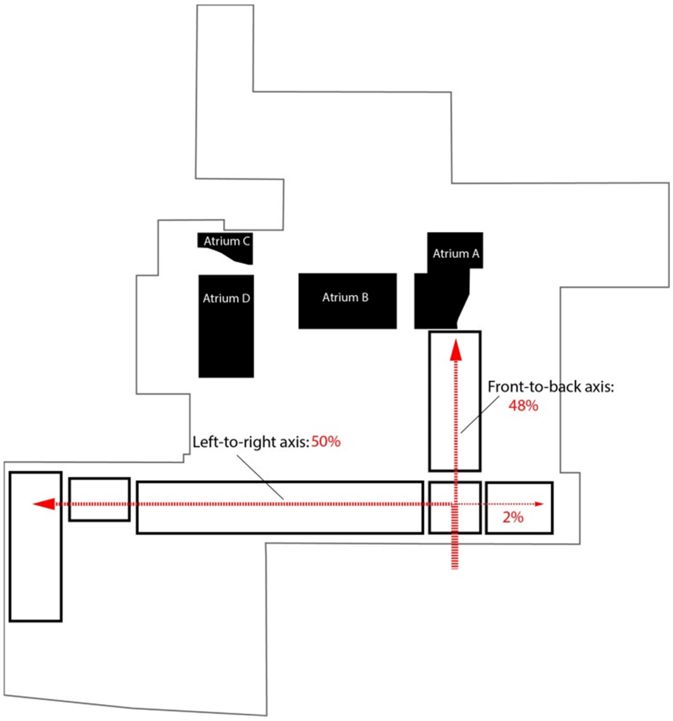
Pattern 'a' seems to be the outcome of a landmark, a tall sculpture situated at the end of the front-to-back axis, visible from the entrance, and the natural light entering from the skylight over Atrium A. Pattern 'b' characterises visitors, who follow a sequential mode of exploration attracted by numerous exhibits along the left-to-right axis. Users that choose this route initially come across the west-side galleries, encountering the atria at a later stage (Lazaridou & Psarra 2015). Thus, pattern 'a' highlights the strong presence of Atrium A with its landmark artwork, which may act as an important attractor. This hypothesis is tested by the virtual experiments described next.

Navigation in the virtual models

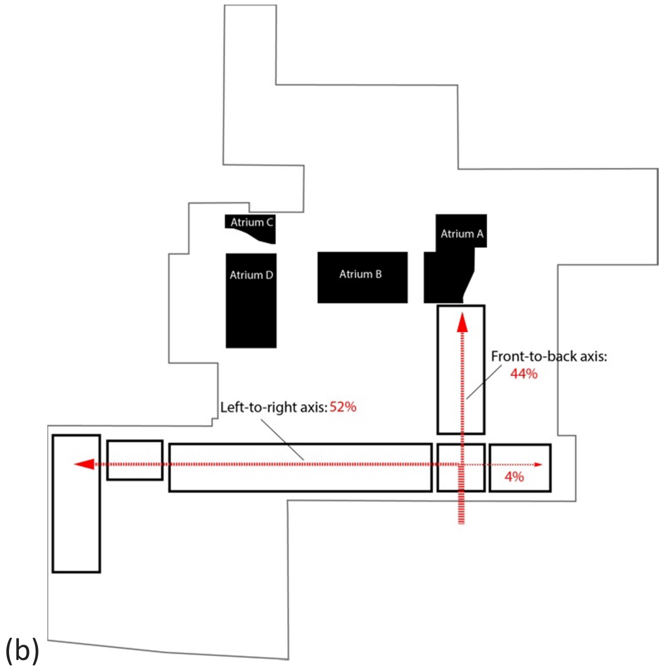
The results of the VR experiments indicate that upon entering the exact virtual model, 52% of the participants choose the left-to-right axis, 44% the front-to-back axis and 4% the right side of the museum (Figure 5). In the modified model, the majority of users (64%) turn to the left-to-right axis and only 24% of them use the front-to-back axis, while 12% turn to the right (Figure 5, Table 2). Real movement presents similar results to those observed in the virtual exploration in the exact model than with the paths in the modified model. Atrium A and the landmark statue seem to be significant attractors of paths in the exact model as in the real building.

Route choices	Front-to-back axis	Left-to-right axis	Right
Real museum	48%	50%	2%
Exact model	44%	52%	4%
Modified model	24%	64%	12%

Table 2. The percentages show the route decisions upon entering the ground floor of the museum.



(a)



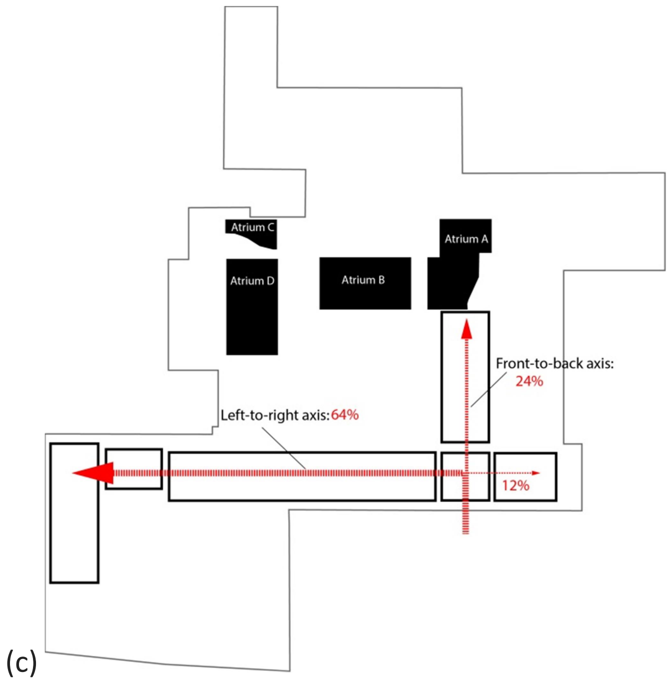


Figure 5. Diagrams illustrating the directions chosen by the participants upon entering the museum. (a) real movement; (b) virtual movement in the exact model; (c) virtual movement in the modified model. Patterns 'a' and 'b' initiate from the entrance (ground floor) and split towards the front-to-back axis and the left-to-right axis respectively.

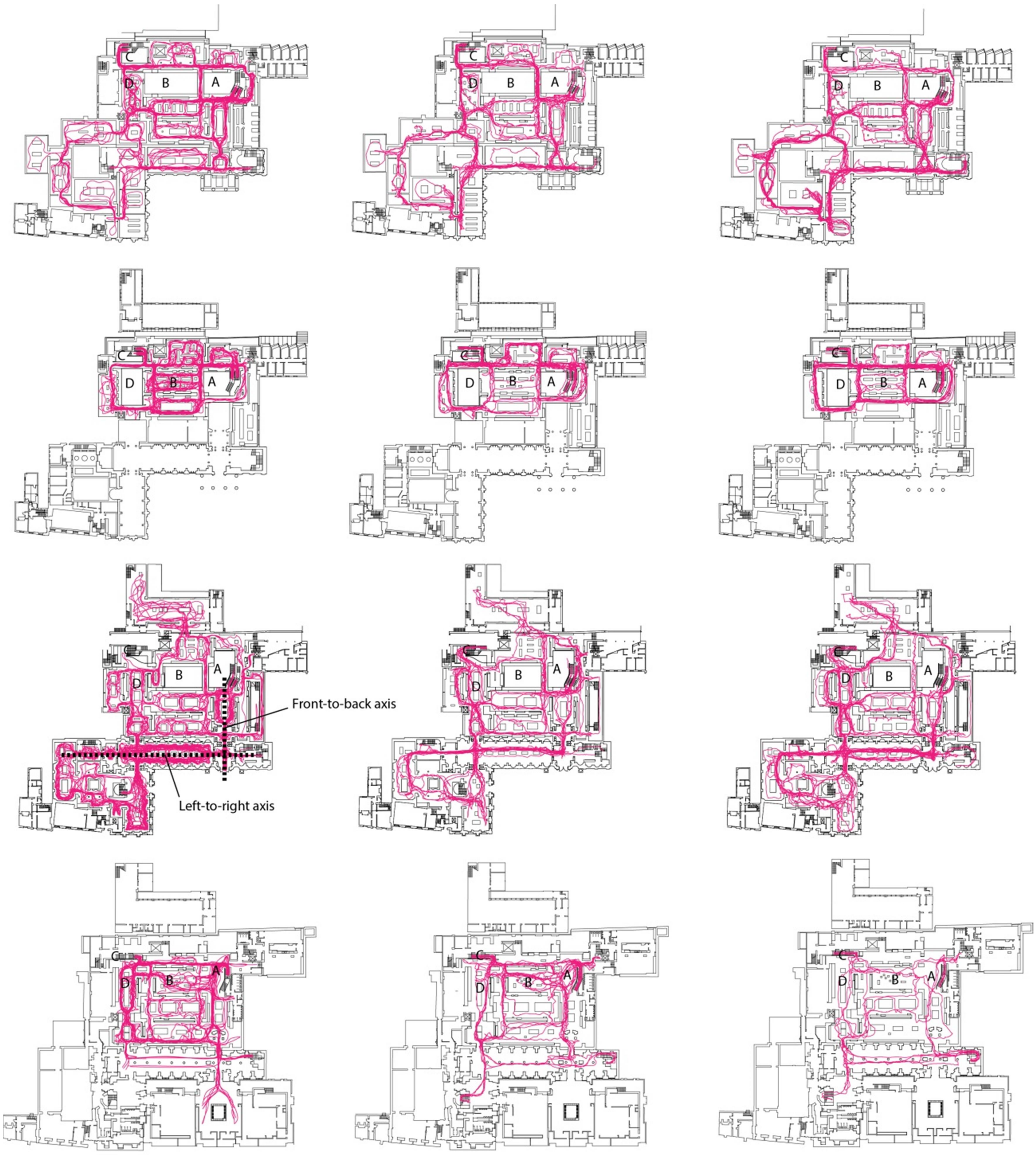


Figure 6. Real (left) and virtual traces in the exact model (middle) and in the modified one (right) of the Ashmolean Museum.

Another finding concerns peoples' vertical movement or the average rate of people changing floor while encountering an atrium for the first time. In the exact model, 60% of users on the ground floor change level upon reaching an atrium, compared to 46% in the modified model (Table 3). This effect is stronger on the ground floor than on the rest of the floors, possibly illustrating that 3D views impact navigation when encountered for the first time. Another reason may be that users, once accustomed to virtual navigation, prefer to move first horizontally, to cover the majority of spaces, and later vertically, to the other floors.

Exact model	Average rate of changing level
Basement	40%
Ground Floor	60%
First Floor	48%
Second Floor	44%
Modified model	
Basement	25%
Ground Floor	46%
First Floor	36%
Second Floor	4%

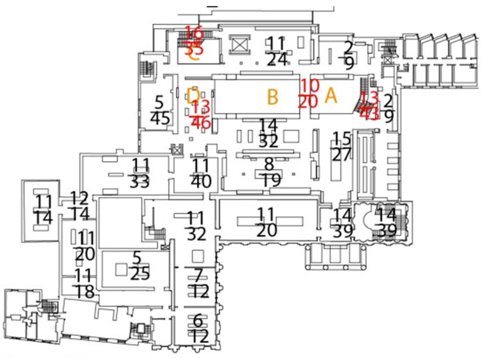
Table 3. Average rate of changing level in the virtual models when users encountered for the first time a staircase inside an atrium.

As previously described, participants were asked to 'return to the entrance' upon completing their virtual navigation. Looking into the positioning and size of atria, Atria A and C are strongly different from each other. Atrium A is situated at the back part of the building distributing movement to its surrounding galleries. In contrast, Atrium C is located at the far end of the layout, mostly facilitating vertical circulation. The virtual experiments show that in the exact model, 68% of the participants use the stairs of Atrium A to return to the ground floor, and 33% use Atrium C. In contrast, in the modified model, 57% of people use the stairs of Atrium A and 43% Atrium C. In the exact model, the views offered from Atrium A attract a higher number of users to itself when changing level, illustrating that it acts as an orientation and reference point. However, when closed off, it loses its strong role in navigation. Atrium C, in the exact model, does not attract high rates of movement (33%), compared to the modified model, where it plays a more significant role (43% of users). The difference in the percentages of visitors choosing Atrium A over C illustrates the influential role of the three-dimensional connections in terms of visibility and accessibility offered by Atrium A.

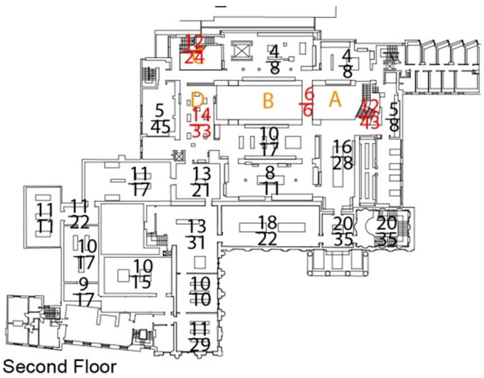
The average amount of time people spend navigating the exact model (9.9 minutes) is very close to that of the modified model (10 minutes). The total time spent additively by all participants exploring the atria and the galleries surrounding them in the exact model is 35 minutes (No convex spaces: 1-4, 12-15, 28-29, 36-40). In the modified model it is 22.7 minutes (Figure 7). Additionally, in the exact model, 75% of the participants explore the galleries located deeply inside the museum, as opposed to the modified model, where only 38% of people access these galleries. These results show that the crossviews overlooking the galleries and the displays of the museum offered by the atria attract movement and structure navigation around them.

In order to determine the ways in which galleries structure movement, depending on their proximity with the atria, we use two measures developed by Choi (1997). These are: Tracking Score (Ts), quantifying the number of users visiting each space in the building; Tracking Frequency (Tf), referring to the number of times each space is visited (Figure 8). The outcomes show that, in the exact model, participants are mostly attracted by the core galleries (Ts=343) - those surrounding the atria - and less by the front galleries (Ts=207). On the contrary, in the modified model, people concentrate in the front galleries (Ts=375), away from the core galleries (Ts=221). This proves that in the absence of three-dimensional vistas, navigation in the modified model is significantly shaped by the use of local-scale visual cues in single-storey high galleries.

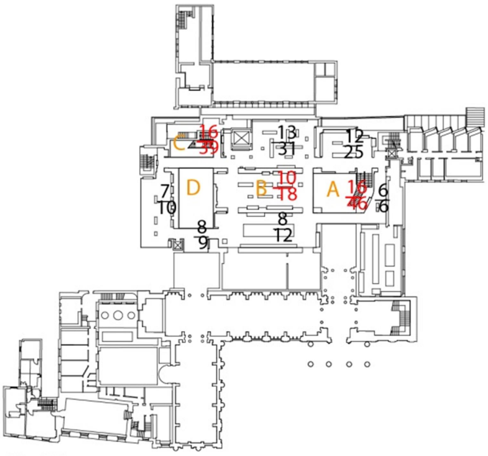
Figure 7. Diagram (left) showing the classification of the convex spaces for each floor. Histograms (right) illustrating the relationship between the convex spaces and the time (minutes) spent by all participants inside the virtual models.



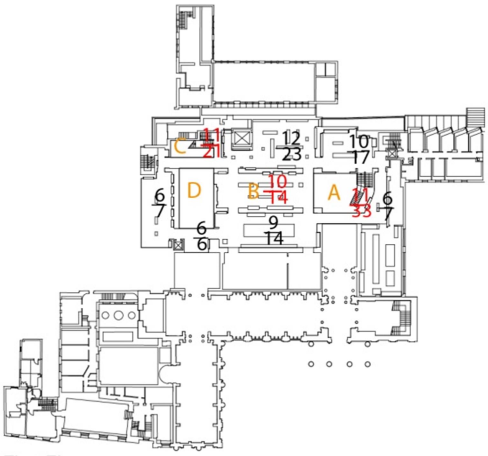
Second Floor



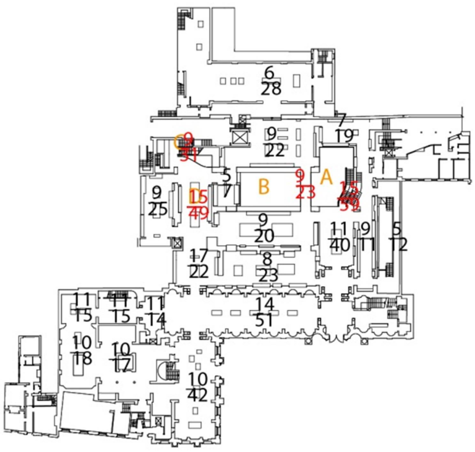
Second Floor



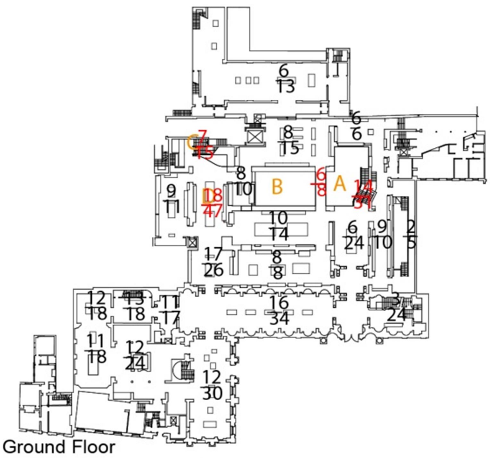
First Floor



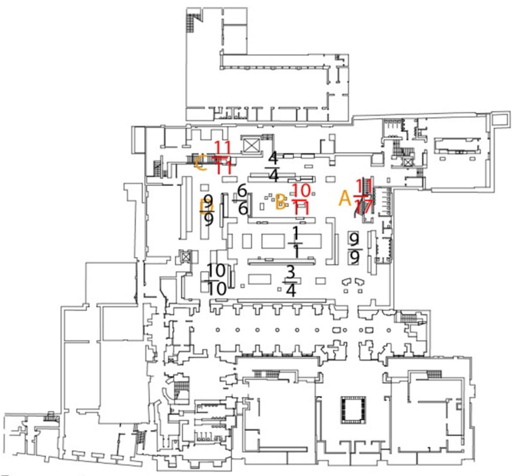
First Floor



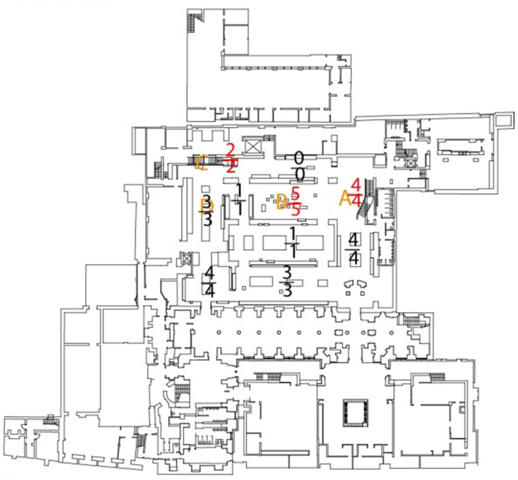
Ground Floor



Ground Floor



Basement



Basement

Figure 8. The tracking score (upper value) and the tracking frequency (lower value) values in the exact (left) and in the modified model (right). The values in red illustrate the amount of users and visits around the atria and in black, the values in the galleries.

Head Movement Findings

Head orientation in the virtual models can capture users' scanning of the architectural characteristics of space and direction. Figure 9 illustrates the locations where head movement occurred mostly in the virtual models. Participants, in the exact model, turn their heads horizontally on the passages next to Atria A, B and C and D as well as at the intersection point between the left-to-right and the western axis (Table 4). In the modified model, there are no clearly defined concentrations of head movement. On the contrary, it seems that they are dispersed throughout the whole layout.

The frequency of head turns differs in the two models. In the exact model, participants turn their heads 1373 times in total, as opposed to the modified model, where head-turns are nearly twice as frequent (2431 times) (Table 4). More analytically, in the exact model, users turn their heads horizontally 432 times on the ground floor and 378 times on the second floor. In the modified model, they turn their heads horizontally 926 times on the ground floor and 878 times on the second floor (Table 4). Considering that head movement indicates browsing as well as seeking route direction, this striking difference clearly shows that in the exact model, participants look around and search for direction in fewer spaces and fewer times than in the modified model. Therefore, the modified model appears to be a more difficult environment to navigate, since participants constantly check their position horizontally.

Horizontal head movement	SUM (times)
Basement	
Exact model	251
Modified model	286
Ground floor	
Exact model	432
Modified model	926
First floor	
Exact model	312
Modified model	341
Second floor	
Exact model	378
Modified model	878
SUM Exact model	1373
SUM Modified model	2431

Table 4. Total number of times the participants moved their head along the horizontal direction in the exact and the modified models.

Head movement along the vertical direction indicates that in the exact model participants look up and down more often (506 times) compared to the modified model (284 times) (Table 5). In the latter, head movement is mainly concentrated at the entrance and the double-height gallery on the ground floor, where the left-to-right axis intersects with the western axis (Table 5, Figure 10). The high number of head movements along the vertical direction in close proximity to the atria in the exact model confirms our initial expectation that atria attract people's attention. Combined with the strong navigational pull of atrium A, the rates related to head movement suggest that atrium A has a considerable influence on route direction and choice.

The results indicate a difference between the exact and modified model in relation to head movement, along the horizontal and vertical directions (Table 4, Table 5). In the exact model, participants turn their heads, browsing along the horizontal direction less frequently and on specific locations for making route decisions, yet scan extensively the atria along the vertical dimension. Users in the modified model act in the opposite way, frequently scanning the layout horizontally, and less frequently engaging with the third dimension. Atria in the exact model seem to influence people, in terms of their route direction and scan for spatial information. They also seem to ease navigation and orientation in a way that users are able to plan their next steps and position themselves in the circulation structure. On the contrary, the absence of atria creates a more sequential layout. In this case, users seek orientation and direction, engaging with the horizontal structure of space in the absence of large-scale views.

Vertical head movement (times)	SUM
Exact model	506
Modified model	284

Table 5. Total number of times the participants moved their head along the vertical direction in the exact and the modified models.

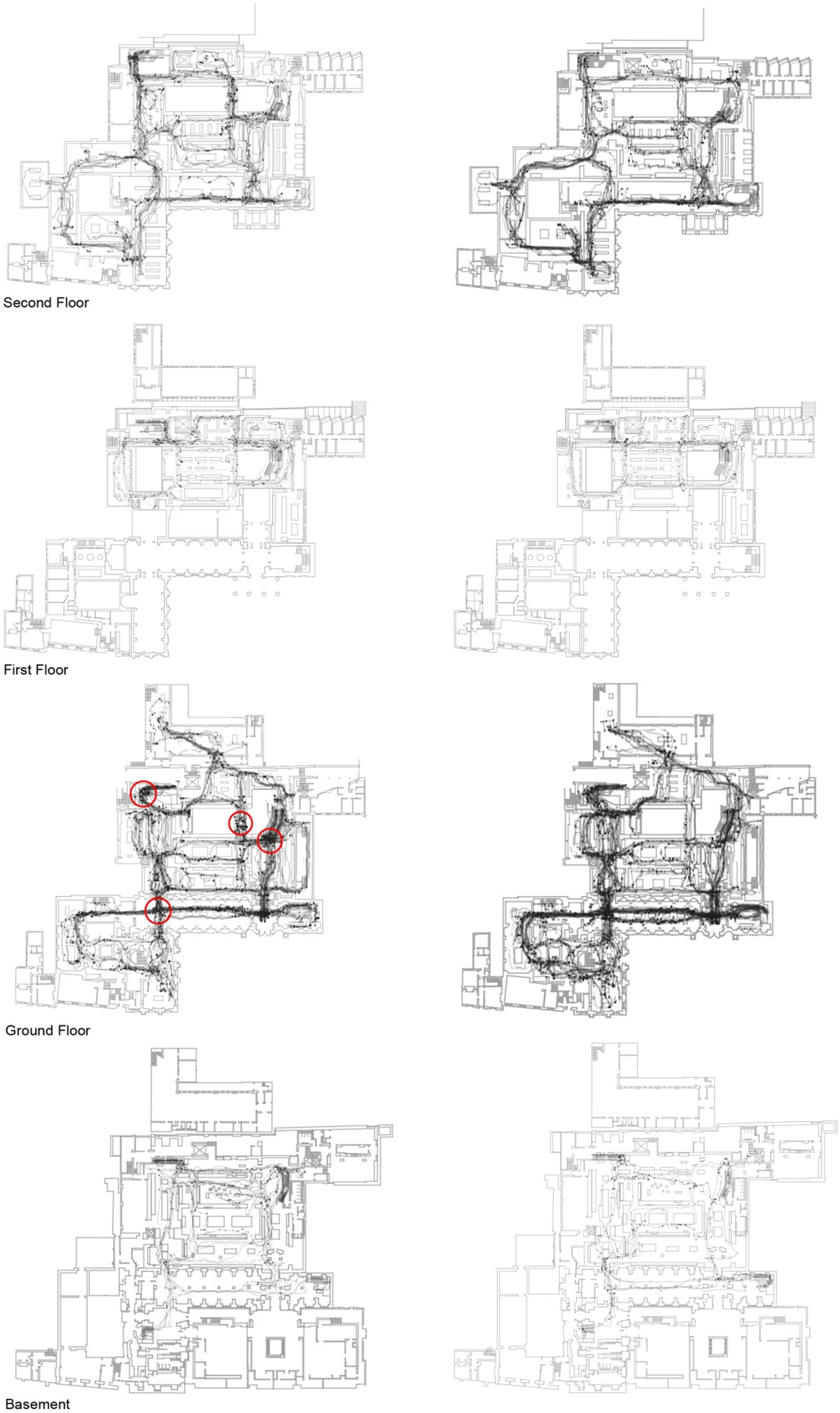


Figure 9. Head movement (horizontal axis) in the exact model (left) and the modified one (right).

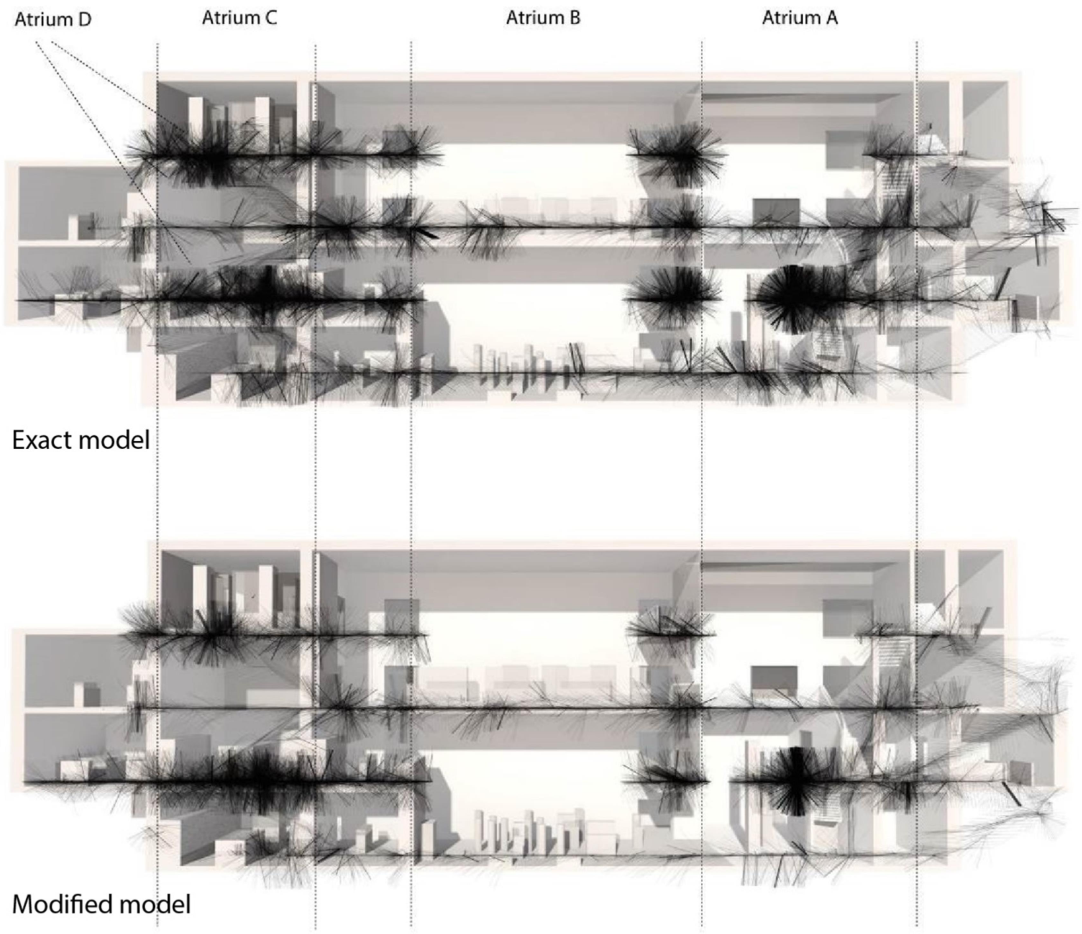


Figure 10. Vertical head movement of all participants overlaid on the three-dimensional sections of the exact and the modified virtual models, using the output data from the virtual tracking.

Summary and discussion

The research concludes with the following findings:

Visitors in the real Museum and participants of the VR experiment using the exact model of the building were attracted towards the atria and were better oriented. The two groups of people also made similar route choices with their initial spatial decisions illustrating relevant percentages. Therefore, the atria play a significant role in nudging movement in particular directions and affect the ease of navigation choices.

Paths in the virtual models were different, although the circulation structure remained the same. In the modified model, users equally cover all spaces while seeking direction more frequently, as the patterns of their movement and head turns indicate. Further, in the exact model participants change floor through Atrium A and opt for different stairs on their way out. There is a clear effect of atria on free exploration, as they offer a high degree of visual information and vertical accessibility across different floors. Therefore, the research sheds light on common architectural intuition confirming that voids inform three-dimensional exploration, acting as reference and orientation spaces.

Findings related to head movement show that users in the exact model turned their heads horizontally fewer times than those visiting the modified model. Vertical connections in the exact model were explored mostly in proximity to the atria while horizontal scanning was more frequent in the modified model. The intensity and frequency of head movement along the horizontal direction in the modified model, illustrates users' need for orientation. Extensive head movement along the vertical dimension combined with head movement on the horizontal plane, occurring in critical points adjacent to the atria in the exact model highlight the supportive role of these spaces in spatial orientation, and, at times, engagement with the 3D architecture of the building.

The research captures evidence of human engagement with the three-dimensional design with regard to free exploration. Statistical correlations between spatial configuration and human movement form the method used to justify inferences about the impact of the layout on patterns of movement (Haq & Zimring 2003; Hillier et al. 1996; Rohloff et al. 2009; Penn 2003; Peponis et al. 1990; Peponis et al. 2003; Zimring & Conroy Dalton 2003; Psarra 2005; Psarra 2007; Psarra 2009). By recording real-time movement in association with head direction, this study captures the detailed relationship of atria to route choices and the ways in which people engage with the layout. In this way, the role of space in free exploration is addressed by observing and measuring human navigation.

There are potential limitations encountered in the present study. Head movement can have many purposes apart from navigation. For example, the displays in the galleries, the architecture of the building and the effect of lighting can trigger head turning and affect route choice, due to participants' interest in the above features and not only in the actual layout. Additional variations of layouts and displays can be tested in future research using VR, by changing the lighting conditions of the environment and the positioning of the exhibits. Regression analysis testing the relationship between spatial variables and rates of visitor paths, gaze direction and head turns could also be used to understand the impact of atria on navigation.

The current results can be regarded as a starting point for further research that includes assessing navigation performances in complex buildings. The outcomes of the study on free exploration and head movement partly reinforce existing knowledge related to the work of Einhäuser et al. (2007), who examined the head-eye coordination in the exploration of various environments (forest, train station, apartment). The researchers illustrated that participants' head and eye movements occur along the cardinal axes, while the predominance of vertical or horizontal movements is influenced by the environment. This study's findings can be further explored through the testing of additional factors, such as participants' responses to variations of atria locations, orientation and exploration techniques. In conclusion, although museums consist of numerous spatial variables that can influence human navigation, our study places emphasis on the need for researchers to account for three-dimensional spatial configuration, and for architects to pay attention to the role of atria and vertical connections in buildings.

Acknowledgments

The authors are grateful to the participants of the virtual reality experiments and to Dr Petros Koutsolambros for the implementation of the VR script. The authors would also like to thank Professor John Peponis at the Georgia Institute of Technology for his thorough review, theoretical and analytical insights.

Funding

This work was supported by the "IKY - State Scholarships Foundation" (ESF) NSRF, 2007-2013; and The Bartlett School of Architecture, UCL.

References

Barton, Kevin R., Deltcho Valtchanov, and Colin Ellard. 2014. "Seeing beyond your visual field. The influence of spatial topology and visual field on navigation performance." *Environment and Behavior, 46(4),* 507-529. https://doi.org/10.1177/0013916512466094

Benedikt, Michael L. 1979. "To Take Hold of Space: Isovists and Isovist Fields." *Environment and Planning B: Planning and Design 6(1),* 47–65. https://doi.org/10.1068/b060047

Bishop, Ian D., and Bernd Rohrmann. 2003. "Subjective responses to simulated and real environments: a comparison." *Landscape and Urban Planning*, *65(4),* 261-277. https://doi.org/10.1016/S0169-2046(03)00070-7

Bowman, Doug A., Ernst Kruijff, Joseph J. LaViola, Jr., and Ivan Poupyrev. 2004. *3D User Interfaces: Theory and Practice.* California: Addison-Wesley http://www.awprofessional.com

Brandt, Thomas, Markus Huber, Hannah Schramm, Günter Kugler, Marianne Dieterich, and Stefan Glasauer. 2015. "Taller and shorter: Human 3-D spatial memory distorts familiar multilevel buildings." *PLOS ONE 10(10): e0141257.* https://doi.org/10.1371/journal.pone.0141257

Brandt, Thomas, Andreas Zwergal, and Stefan Glasauer. 2016. "3-D spatial memory and navigation: functions and disorders." *Current Opinion in Neurology, 30(1),* 90-97. https://doi.org/10.1097/WCO.0000000000000415

Choi, Y. K. 1997. "The morphology of exploration and encounter in museum layouts." Proceedings of the 1st International Space Syntax Symposium, London, England.

Christou, Chris, Aimilia Tzanavari, Kyriakos Herakleous, and Charalambos Poullis. 2016. *"Navigation in Virtual Reality: Comparison of Gaze-Directed and Pointing Motion Control."* Proceedings of the 18th Mediterranean Electrotechnical Conference MELECON 2016, Cyprus. https://doi.org/10.1109/MELCON.2016.7495413

Coutrot, Antoine, Sophie Schmidt, Lena Coutrot, Jessica Pittman, Lynn Hong, Jan M. Wiener, Christoph Hölscher, Ruth C. Dalton, Michael Hornberger, and Hugo J. Spiers. 2019. "Virtual navigation tested on a mobile app is predictive of real-world wayfinding navigation performance." PLOS ONE, 14(3), e0213272. https://doi.org/10.1371/journal.pone.0213272

Dalton, Nick, Ruth Dalton, Paul Marshall, Iwan Peverett, and Sarah Clinch. 2015. *"Three dimensional Isovists for the Study of Public Displays."* Proceedings of 10th International Space Syntax Symposium. London, England.

Denis, Michel, Pierre-Emmanuel Michon, and Ariane Tom. 2007. "Assisting pedestrian wayfinding in urban settings : Why references to landmarks are crucial in direction-giving." In: Gary L. Allen (ed), *Applied Spatial Cognition: From*

Research to Cognitive Technology, 25–51. Psychology Press https://www.routledge.com

Einhäuser, Wolfgang, Frank Schumann, Stanislavs Bardins, Klaus Bartl, Guido Boening, Erich Schneider, and Peter König. 2007. "Human eye-head co-ordination in natural exploration." *Network (Bristol, England), 18,* 267-97. https://doi.org/10.1080/09548980701671094.

Frankenstein, Julia, Sven Brüssow, Felix Ruzzoli, and Christoph Hölscher. 2012. "The language of landmarks: the role of background knowledge in indoor wayfinding." *Cognitive processing, 13,* Suppl . S165-70. https://doi.org/10.1007/s10339-012-0482-8

Franz, Gerald, and Jan M. Wiener. 2008. "From space syntax to space semantics: A behaviorally and perceptually oriented methodology for the efficient description of the geometry and topology of environments." *Environment & Planning B: Planning and Design*, *35(4),* 574-592. https://doi.org/10.1068/b33050

Gath-Morad, Michal, Leonel Aguilar, Ruth Conroy Dalton, and Christoph Hölscher. 2020. *"cogARCH: Simulating Wayfinding by Architecture in Multilevel Buildings."* 11th Annual Symposium on Simulation for Architecture & Urban Design (SimAUD 2020).

Haq, Saif, and Craig Zimring. 2003. "Just down the road a piece – The development of topological knowledge of building layouts." *Environment and Behavior, 35(1),* 132-160. https://doi.org/10.1177/0013916502238868

Haq, Saif, Glenn Hill, and Adetania Pramanik. 2005. "*Comparison of configurational, wayfinding and cognitive correlates in real and virtual settings*." Proceedings of the 5th International Space Syntax Symposium, 2, 387-405.

Hillier, Bill, and Julienne Hanson. 1984. *The Social Logic of Space*. Cambridge: Cambridge University Press.

Hillier, Bill, Mark Major, Jake Desyllas, Kayvan Karimi, Beatrix Campos, and Tim Stonor. 1996. "*Tate Gallery, Millbank: A study of the existing layout and new masterplan proposal.*" UCL (University College London): London, UK.

Hölscher, Christoph, Tobias Meilinger, Georg Vrachliotis, Martin Brösamle, and Markus Knauff. 2006. "Up the down staircase: wayfinding strategies and multi-level buildings." *Journal of Environmental Psychology 26*, 284-299. https://doi.org/10.1016/j.jenvp.2006.09.002

Hölscher, Christoph, Simon J. Bűchner, Tobias Meilinger, and Gerhard Strube. 2009. "Adaptivity of wayfinding strategies in a multi-building ensemble: The effects of spatial structure, task requirements, and metric information." *Journal of Environmental Psychology*, *29(2),* 208-219. https://doi.org/10.1016/j.jenvp.2008.05.010

Kaynar Rohloff, Ipek, Sophia Psarra, and Jean Wineman. 2009. "*Experiencing museum gallery layouts through local and global visibility properties in morphology: an inquiry on the YCBA, the MoMA and the HMA*." Proceedings of the 7th International Space Syntax Symposium, (ed.) Koch, D., Marcus, L., and Steen, J., Stockholm, KTH.

Kimura, Kazushige, James F. Reichert, Ashley Olson, Omid Ranjbar Pouya, Xikui Wang, Zahra Moussavi, and Debbie M. Kelly. 2017. "Orientation in Virtual Reality Does Not Fully Measure Up to the Real-World." *Scientific Reports, 7(1),* 18109. https://doi.org/10.1038/s41598-017-18289-8

Kuliga, Saskia F., Tyler Thrash, Ruth Conroy Dalton, and Christoph Hölscher. 2015. “Virtual reality as an empirical research tool — Exploring user experience in a real building and a corresponding virtual model.” *Computers, Environment and Urban Systems, 54,* 363-375. https://doi.org/10.1016/j.compenvurbsys.2015.09.006.

Kuliga, Saskia. 2016. “Evaluating user experience and wayfinding behaviour in complex, architectural environments – towards a user-centred approach of building usability.” *PhD Dissertation*. Freiburg.

Lazaridou, Athina, and Sophia Psarra. 2015. *“Experiencing three-dimensional museum environments: An investigation of the Ashmolean Museum and the Museum of Scotland”.* Proceedings of the Tenth International Space Syntax Symposium, London: UCL.

Lu, Yi, and John Peponis. 2013. “Exhibition visitors are sensitive to patterns of display covisibility”. *Environment and Planning B: Planning and Design, Vol. 40.* https://doi.org/10.1068/b39058

Lu, Yi, and Yu Ye. 2017. “Can people memorize multilevel building as volumetric map? A study of multilevel atrium building.” *Environment and Planning B: Urban Analytics and City Science*, *46 (2)*, 225-242. https://doi.org/10.1177/2399808317705659

Montello, Daniel R., and Herbert L. Pick. 1993. “Integrating Knowledge of Vertically Aligned Large-Scale Spaces.” *Environment and Behavior, 25(3),* 457-484. https://doi.org/10.1177/0013916593253002

Morello, Eugenio, and Carlo Ratti. 2009. "A Digital Image of the City: 3D Isovists in Lynch's Urban Analysis." *Environment and Planning B: Planning and Design 36:* 837–53.

Natapov, Asya, Saskia Kuliga, Ruth Conroy Dalton, and Christoph Hölscher. 2019. "Linking building-circulation typology and wayfinding: design, spatial analysis, and anticipated wayfinding difficulty of circulation types." *Architectural Science Review 63 (1),* 34-46. https://doi.org/10.1080/00038628.2019.1675041

Penn, Alan. 2003. "Space syntax and spatial cognition: Or, why the axial line?" *Environment and Behavior*, *35*, 30-65. https://doi.org/10.1177/0013916502238864

Peponis, John, Craig Zimring, and Yoon Kyung Choi. 1990. "Finding the building in wayfinding." *Environment and Behavior*, 22(5), 555-590. https://doi.org/10.1177/0013916590225001

Peponis, John. 1993. "Evaluation and formulation in design: The implications of morphological theories of function". *Nordisk Architekturforskning,* 2, 53-61.

Peponis, John, Ruth Conroy Dalton, Jean Wineman, and N.S. Dalton. 2003. "*Path, theme and narrative in open plan exhibitions settings*." Proceedings of the 4th International Space Syntax Symposium, London.

Peponis, John. 2016. "The Space syntax of intelligible communities." In: Hunter, R. H., Anderson, L. A., and Belza, B. L. (Eds.) *Community Wayfinding: Pathways to Understanding*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-31072-5_3

Portman, Michelle E., Asya Natapov, and Dafna Fisher-Gewirtzman. 2015. “To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning.” *Computers, Environment and Urban Systems, 54,* 376-384. https://doi.org/ 10.1016/j.compenvurbsys.2015.05.001.

Psarra Sophia, and Tadeusz Grajewski. 2000. “Architecture, narrative and promenade in Benson + Forsyth’s Museum of Scotland.” *Architectural Research Quarterly*, *4(02)*, 123-136. https://doi.org/10.1017/S1359135500002578

Psarra, Sophia. 2005. “Spatial culture, wayfinding and educational message - the impact of layout on the spatial, social and educational experience of visitors in museums and galleries.” In: S. Macleod (ed.), *Reshaping museum space: architecture, design, exhibitions*, 78-94. UK: Taylor & Francis.

Psarra, Sophia. 2009. *Architecture and narrative: The formation of space and cultural meaning*: Routledge.

Saxon, Richard. 1993. *The Atrium comes of age*. London: Longman.

Turner, Alasdair. 2001. *“A program to perform visibility graph analysis.”* Proceedings of the 3rd Space Syntax Symposium. Atlanta.

Turner, Alasdair, and Alan Penn. 2002. “Encoding natural movement as an agent-based system: an investigation into human pedestrian behavior in the built environment.” *Environment and Planning B*, *29 (4),* 473 - 490. https://doi.org/10.1068/b12850

Varoudis, Tasos, and Sophia Psarra. 2014. “Beyond two dimensions: architecture through three dimensional visibility graph analysis.” *Journal of Space Syntax, 5(1):* 91-108.

Werner, Steffen, and Paul Long. 2003. “Cognition meets Le Corbusier - Cognitive principles of architectural design.” In: Freksa, C., Brauer, W., Habel, C., Wender, K.F. (Eds.). *Spatial Cognition III. Routes and Navigation, Human Memory and Learning, Spatial Representation and Spatial Learning*. Springer Berlin Heidelberg.

Wiener, Jan M., Simon J. Buechner, and Christoph Hölscher. 2009. “Taxonomy of human wayfinding tasks: A knowledge-based approach.” *Spatial Cognition & Computation”, 9(2)*, 152-165. https://doi.org/10.1080/13875860902906496

Zimring, Craig, and Ruth Conroy Dalton. 2003. “Linking objective measures of space to cognition and action.” *Environment and Behavior*, *35(1),* 3-16. https://doi.org/10.1177/0013916502238862

Weblinks

Autodesk Memento. https://memento.autodesk.com/about, 24 February 2016