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SPATIAL NAVIGATION IN REAL AND VIRTUAL MULTI-LEVEL MUSEUMS

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ABSTRACT

Atria in public buildings, such as museums and cultural environments, serve the purposes of architectural expression as well as spatial navigation. This is clearly seen in numerous existing buildings and modern extensions, such as in the Ashmolean Museum in Oxford, the most recent masterplan of which uses atria to link the old with the new sectors of the building, attract human activity and facilitate three-dimensional exploration. Until recently, most space syntax studies on navigation focused on route choices and spatial characteristics in two dimensions, consequently by-passing the effect of the third dimension on spatial exploration. Although common sense acknowledges a link between three-dimensional design and human movement, there is no substantial research on how the third dimension relates to patterns of exploration. Using the Ashmolean Museum as the main focus study, this paper explores the relationship of actual human movement (visitors' paths), virtual movement (VR) and spatial structure (space syntax), in order to understand how the multi-storey complex environment impacts on users' free exploration. The findings suggest that verticality three-dimensional visibility, have a significant effect on how people move in a museum setting. Virtual experiments including spatial alterations of the volumetric structure of the Ashmolean clearly show the impact of the third dimension on path selection and configuration as well as gaze direction. This paper can inform three-dimensional architectural design with the goal of creating user-friendly buildings. The ultimate aim is to provide principled understanding of the variability of three dimensional design and cognitive dimensions in museum buildings for the public.

KEYWORDS

Museums, spatial navigation, virtual reality, space syntax, atria

1. INTRODUCTION

The paper explores how the three-dimensional design of atria museums affects the ways humans experience these environments. The first part of the study includes a detailed description of how the experiments were set up, organised and performed, describing the three-dimensional model, apparatus, virtual scenarios, processes and participants. The second section compares the virtual navigation patterns to those paths observed in real visits. In addition, the head movements 'visitors' make while exploring virtual environments are discussed. The primary aim is to explore and calculate head movement data to shed light on the effect of the third dimension on navigation. In this way, the paper moves between scales of analysis, from the aggregate level to the micro scale spatial decisions that are taken progressively while moving.

To start with, atria seem to be endowed with a cognitive function, as orientation and reference points within complex buildings. A courtyard or an atrium, as Werner and Long (2003) argue, can act as an orientation point within a global frame of reference. In addition, Choi (1997, p. 2) describes how atria 'offer a variety of possibilities for peoples' co-awareness due to the amount of vistas that are offered'. In other words, the architectural layout, when experienced from a multitude of points with the aid of the voids, would seem to have a direct impact on navigation.

Space syntax is used to analyse the two-dimensional properties of the layout, revealing and predicting patterns of pedestrian movement. It sheds light on navigation processes and wayfinding (Broesamle et.al 2009; Hoelscher and Broesamle, 2007; Penn, 2003; Peponis, 1993; Peponis et al., 2003; Peponis and Conroy Dalton, 2004; Psarra, 2009). In addition, agent-based models are used to study movement patterns (Turner and Penn, 2002), which are further correlated with observed navigation. These syntactic methods highlight the relationship between the two-dimensional layout and human exploration. Nevertheless, there is an important factor missing from its framework: this is the effect of the third dimension on navigation.

Although the existing literature is rich in theoretical and methodological background, it does not provide any rigorous account of the ways multi-level environments relate to the overall navigation paths structured by their layouts. In addition, most approaches focus on wayfinding. As Montello and Pick (1993) and Hoelscher et al. (2009) argue, most research on wayfinding and large-scale complex spaces has focused on two-dimensional layouts with isolated floor levels. However, the real world is three-dimensional, something that needs to be further explored. Other researchers have tried to bridge this gap, by investigating the role of vertical access points in shopping complexes (Passini, 1984), or estimating distances between spaces located on different floors (Foley and Cohen, 1984). Hoelscher et al. (2007) studied how experienced and inexperienced human subjects, in terms of their familiarity with the building, navigate inside the multi-level layout. The users reported wayfinding problems regarding the lack of visual access to vertical points of circulation and incongruent floor layouts. In addition, Hoelscher et al. (2009) examined wayfinding strategies in complex buildings, showing that users first move horizontally inside the building towards the target area and thereafter change floor level to reach their goal. The present study will focus on the ways free exploration is structured in multi-level museums.

For this reason, virtual reality (VR) is used to capture the three-dimensional factor on exploration. Numerous researchers (Bishop and Rohrmann, 2003; Dalton, 2001; Haq et.al, 2005; Franz and Wiener, 2008) have shown that virtual stimuli are a reliable tool to capture real-world behaviours. Building upon existing research, the paper aims to implement aspects of three-dimensionality in relation to navigation and visitors' free exploration, unexamined by other studies. These will be addressed with spatial alterations, related to the use of the third dimension in museum layouts, and the impact of atria on navigation.

Thus, the paper will explore the following research questions: Is there an impact of atria as well as the three-dimensional architectural design on visitors' patterns of movement and exploration?; b. how much do spatial changes related to the atria account for different navigation patterns? c. to what extent is virtual navigation similar to real exploration within a multi-level virtual environment? The overall aim is to gain a better understanding of the impact of the third dimension on human experience.

To this extent, the Ashmolean Museum is selected as a case study for the virtual reality experiment. Comprising of four atria that are tightly embedded within the spatial structure of the galleries, the museum provides a solid ground for exploring the impact of the voids and the third dimension on how people navigate inside exhibition environments.

2. DATASETS AND METHODS

SPATIAL CHARACTERISTICS OF THE MUSEUM LAYOUT

The Ashmolean Museum is situated on Beaumont Street in Oxford, United Kingdom. It was designed and built by Charles Robert Cockerell (1845). Since then, it has undergone a succession of additions, the most recent being in 2009, by Rick Mather Architects. The museum has a floor area of approximately 3,900m². The architectural design for the new extension, with its insertion of numerous atria, has introduced a significant number of transparent glazed facades enhancing panoramic views. The mix of double-height and single-height galleries, as well as the staircases and the bridges that traverse the double-height volumes, provide a multiple array of vistas into other galleries (Figure 1). The building consists of four differently sized and shaped atria located in the new extension at the rear of the museum (Figure 1). Specifically, the positioning of the staircases inside atria A and C provides vertical links to the rest of the floors. Further, two major routes, designed by Cockerell, intersect at the entrance and connect the various spaces. The 'Main' axis is at right angles to the Cockerell axis, connecting the entrance with atrium A. The 'Cockerell' axis, linking the entrance with the Egyptian collections, is immediately upon entering and turning to the left. A third axis, the 'Western', links together the galleries located on the west side of the museum, with atrium C at its far end.

3. NAVIGATION PATHS IN THE REAL ASHMOLEAN

Initially, in order to understand how the building's design relates to the actual movement patterns, a detailed observation study was conducted. 50 people per floor were observed for all floors. The tracking lasted for a maximum of 1 hour for each subject. When a visitor changed floor, the researcher moved on to the observation of the next user.

The analysis of paths reveals two kinds of exploration patterns (Figure 4). Exploration pattern 'a' refers to those visitors who on entering follow the main axis of the building (50%) and encounter the three-dimensional voids A and B. Exploration pattern 'b' concerns the other 50% who turn left to the Cockerell axis and the sequential galleries. These paths unfold three-dimensionally on the other floors and are interfaced around the atria. Thus, they reveal a spatial exploration that has a twofold character: pattern 'a', where three-dimensionality acts as a strong attractor of movement towards the atria, away from gallery spaces; pattern 'b' as a sequential system driving visitors through the gallery spaces and encountering the atria at a later stage in the process. The differences between the two patterns of exploration capture a complementary relationship between the architectural and museological function (Lazaridou and Psarra, 2015).

4. VIRTUAL REALITY

4.1 THE VIRTUAL SCENARIOS

As a next step, virtual experiments were conducted, to capture the role of architectural design and the effect of atria on navigation. The experiments included two different virtual worlds defined as Condition A and Condition B and based on the spatial configuration of the Ashmolean. Condition A was the exact representation of the real building. Condition B was based on Condition A, but with the glass walls or railings surrounding the voids being replaced with opaque walls. Thus, the two-dimensional configuration of the museum remained the same. However, the three-dimensional visibility structure was altered by replacing the transparent surfaces around the atria with opaque walls to test the impact of the atria and the third dimension on navigation (Figure 1).

In addition, Visibility Graph Analysis (VGA) was performed for both Conditions, taking into account permeability and visibility measures. Focusing on the VGA graph in Condition A (Figure 2), the visibility structure extends over the atria. In contrast, visual integration in Condition B is limited due to the closed off voids, while the permeability structure continues to be the same with that of the real museum.

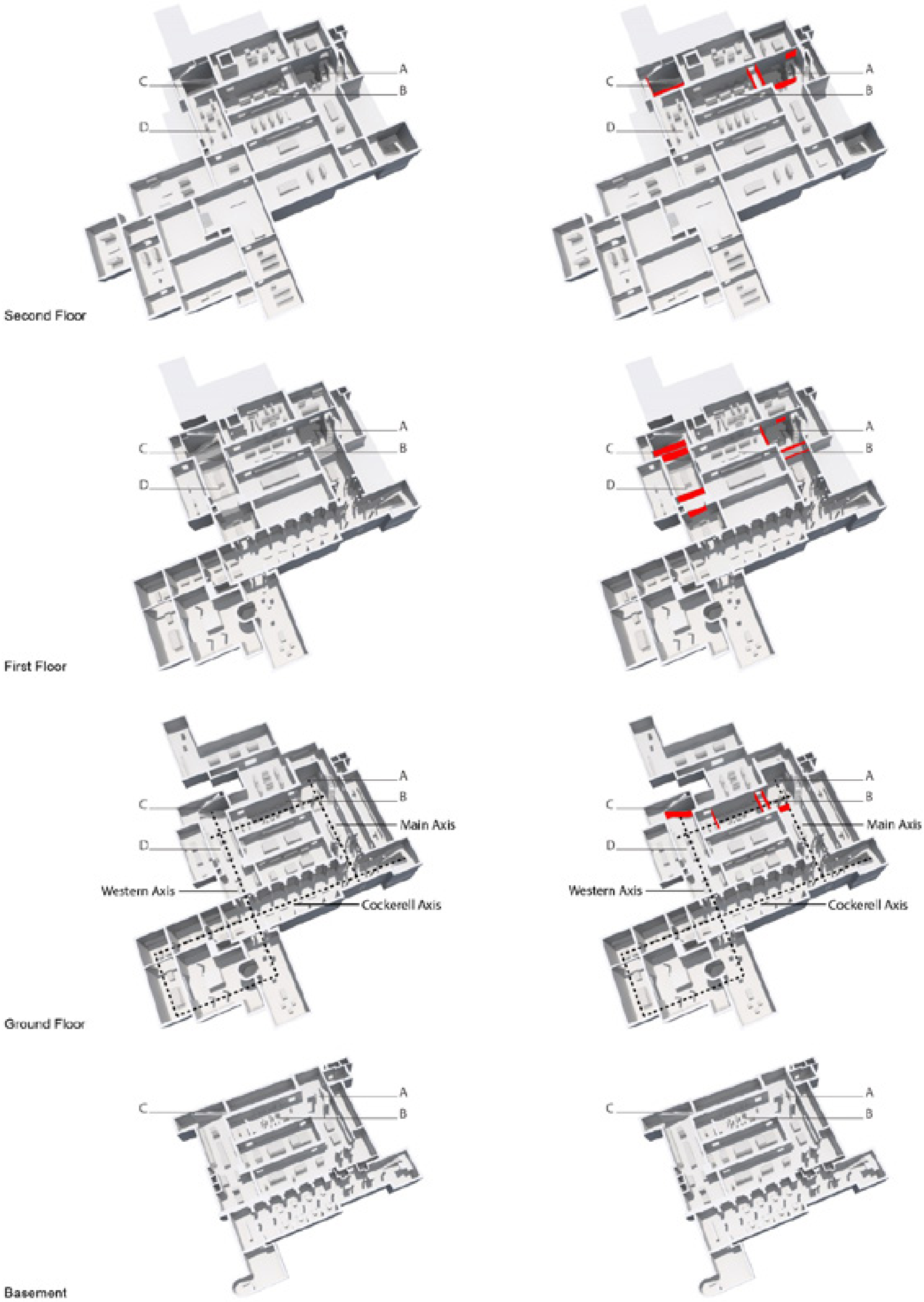


Figure 1 - 3D model of the real Ashmolean or Condition A (left) and Condition B (right). The location of the spatial changes are highlighted in red. Source: Athina Lazaridou.

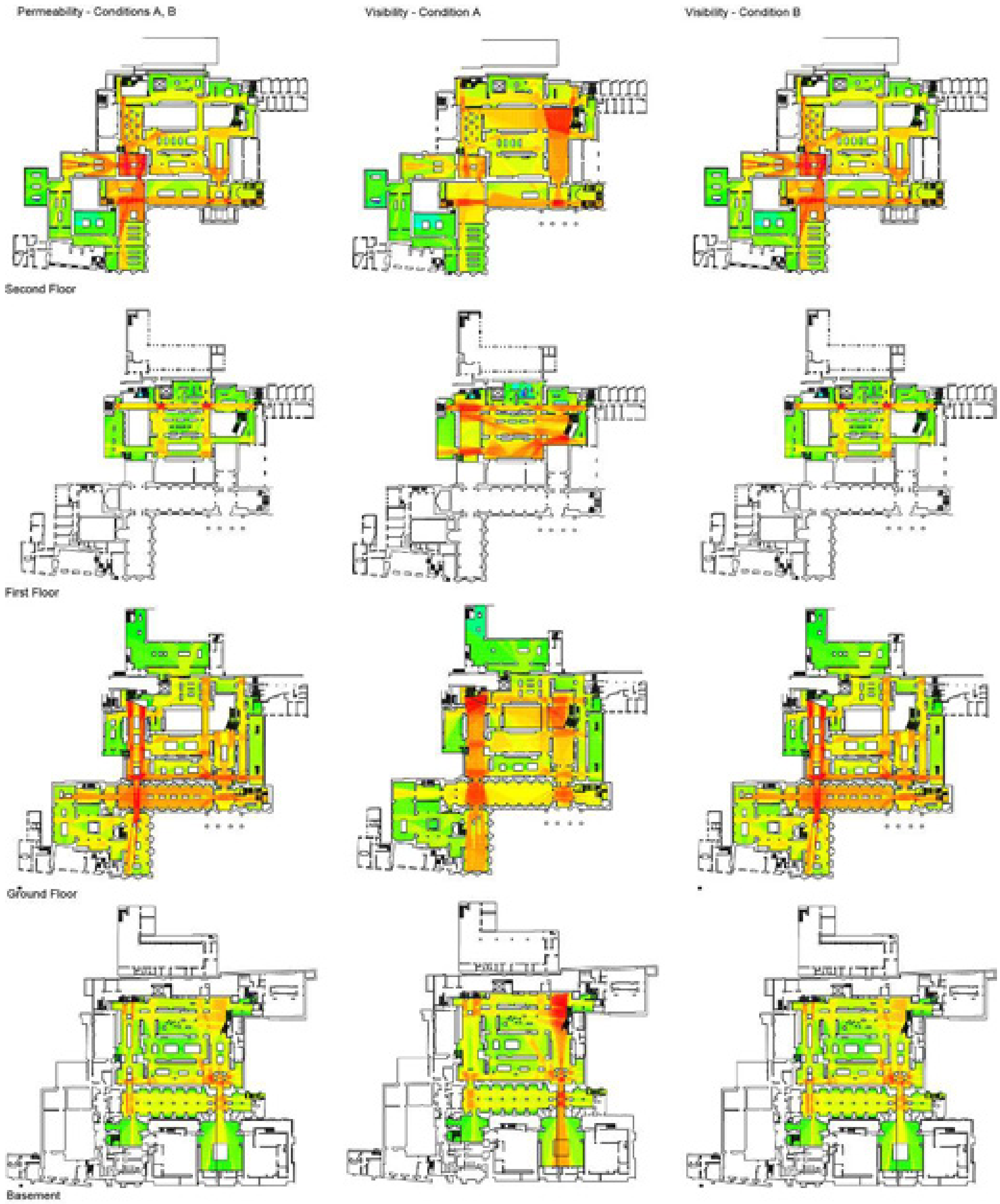


Figure 2 - VGA analysis showing permeability (left) and visibility (middle, right) relations in Conditions A and B.

4.2 VIRTUAL ASHMOLEAN

A virtual three-dimensional model of the Ashmolean Museum was designed in great detail. The 3D visualisation included all four floors, materials, glass facades, views to the city, lights and structural details. Additionally, the researcher employed a 3D scanning process to scan the collections of the building (82 artefacts). The only parameter missing from the 3D virtual world was the presence of other people (Figure 3). The end file was imported in Unity 5.1.2f1, to enable the application of collision effects (no walking through the walls), set up the First Person Controller (height: 1.67, eye height: 1.60 and walking speed: 1.79m/s, no flying or jumping) and control the lighting conditions. An audio was compiled by the researcher from real-world sounds of the museum to simulate the real acoustic conditions. The aim of all this detailed implementation was to make the subjects feel more present, grounded and aware of their virtual presence. 64% of the participants felt that it helped them be more aware of their virtual movement.

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. The paths were recorded ten times per second offering a great amount of precision.

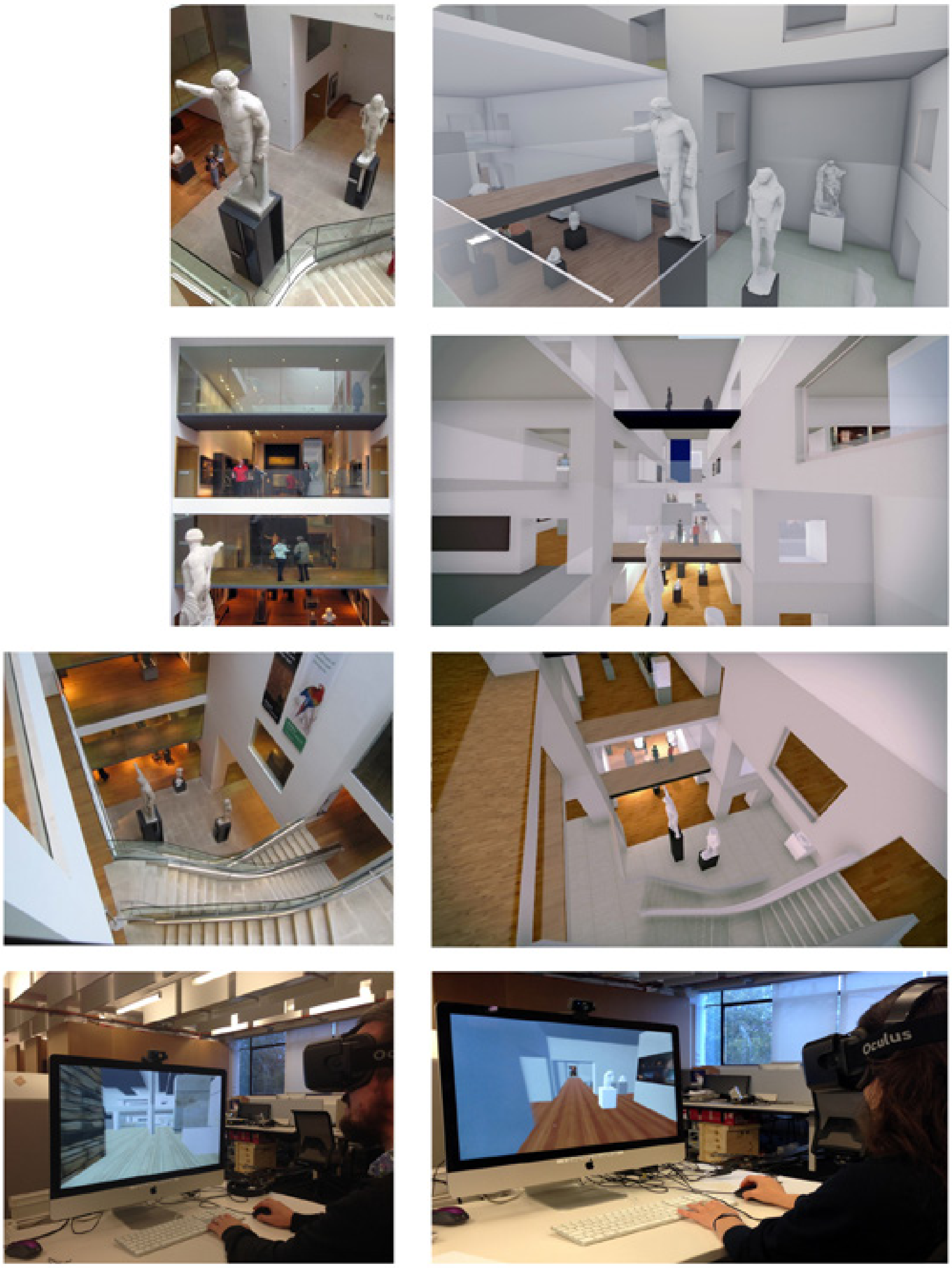


Figure 3 - Views of the real (left) and the virtual environment (right). Last row: Photos of the participants during the experiments.

4.3 THE EXPERIMENT

Users were asked to freely explore the multi-level museum in any way they wanted, acting as if they were visiting the museum in reality. They had to cover as many spaces as possible and when they thought they had explored the whole museum they would need to return to their starting point (entrance). All subjects were initially positioned at the entrance of the building facing towards the external surroundings, to avoid creating any bias and skewing the results regarding their initial route choices. They were not informed about which real world building they would be immersed in. They were given a maximum amount of time (15 minutes) to navigate in the virtual environment. The average period of time subjects spent in the virtual Ashmolean Condition A was 9.9 minutes and in Condition B, 10 minutes.

4.4 THE PARTICIPANTS

Twenty five unpaid participants explored Condition A and twenty five different ones navigated in Condition B. Half of them were female and half male. Half (54%) of the subjects were young adults (18-29), 38% were aged between 30-34 and 8% of them were over 40 years old. The subjects were selected from different disciplines with 36% having an architectural background, 15% being researchers, 22% IT specialists and the rest (27%) coming from the humanities field. The majority were right handed (92%) and 66% of them had no known vision problems. More than half (56%) of the subjects had no previous familiarity with Virtual Reality environments, 42% of them had limited experience and only 2% had regular interaction with this technology. Interestingly enough, 90% of them were familiar with video games on computer screens. Finally, 92% of participants had never visited the Ashmolean Museum before, eliminating any memory effects and biases regarding their movement.

After participating in the experiment, the subjects were asked to answer some additional questions regarding their virtual experience. Half of them (56%) found the use of the VR easy and 30% of them very easy. 98% of them experienced motion sickness, which reduced their navigation endurance.

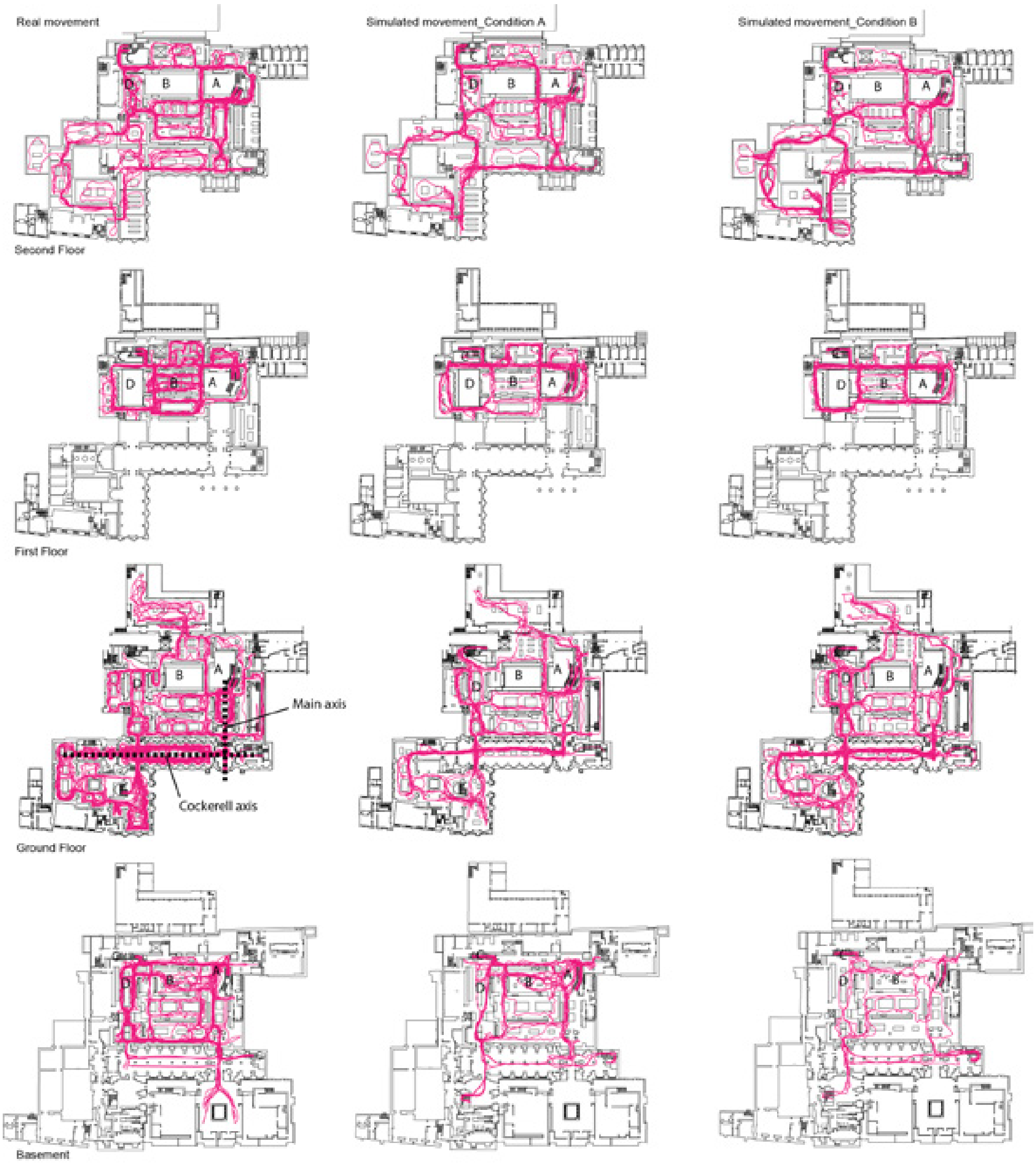
5. RESULTS

5.1 REAL VERSUS VIRTUAL EXPLORATION PATTERNS

The objective of this section is to compare users' performance between real and virtual environments and examine the role of three-dimensionality on exploration. The paths are plotted against the convex breakup of each floor (Figure 4). The comparison between real and virtual movement is realised floor per floor.

Figure 4 shows that the degree of correlation between real and virtual paths in Condition A is strong and positive ($R^2>0.40$, $p<0.01$). This finding demonstrates a clear analogy between virtual movement and real navigation. In contrast, focusing on the relationship between real and virtual navigation in Condition B, the R^2 values highlight weaker parallels. It seems that the three-dimensional alternations in the visibility structure of the museum alter navigation patterns. Thus, the isolation of atria and the third dimension seem to have a significant effect on exploration.

Interestingly, the highest degrees of correlation occur on the basement and on the second floor, when comparing real and virtual traces (Figure 4). This is because no spatial changes occurred on the basement, thus, the correlations remain very close to each other. On the second floor, movement is highly directed due to the spatial configuration of the galleries. Users need to follow the prescribed routes and effectively the relationship between real and virtual exploration is very similar and is less influenced by three-dimensionality.



Correlation R^2	Traces VR A	Traces VR B
Real traces (Basement)	0.75 (p<0.01)	0.72 (p<0.01)
Real traces (Ground floor)	0.40 (p<0.01)	0.28 (p<0.01)
Real traces (First floor)	0.66 (p<0.01)	0.30 (p<0.01)
Real traces (Second floor)	0.86 (p<0.01)	0.74 (p<0.01)

Figure 4 - Correlation matrix. Real (left) and virtual traces for Conditions A (middle) and B (right) in the Ashmolean Museum. Table shows the correlations R-squared between observed and virtual movement (normalised values) in Conditions A and B.

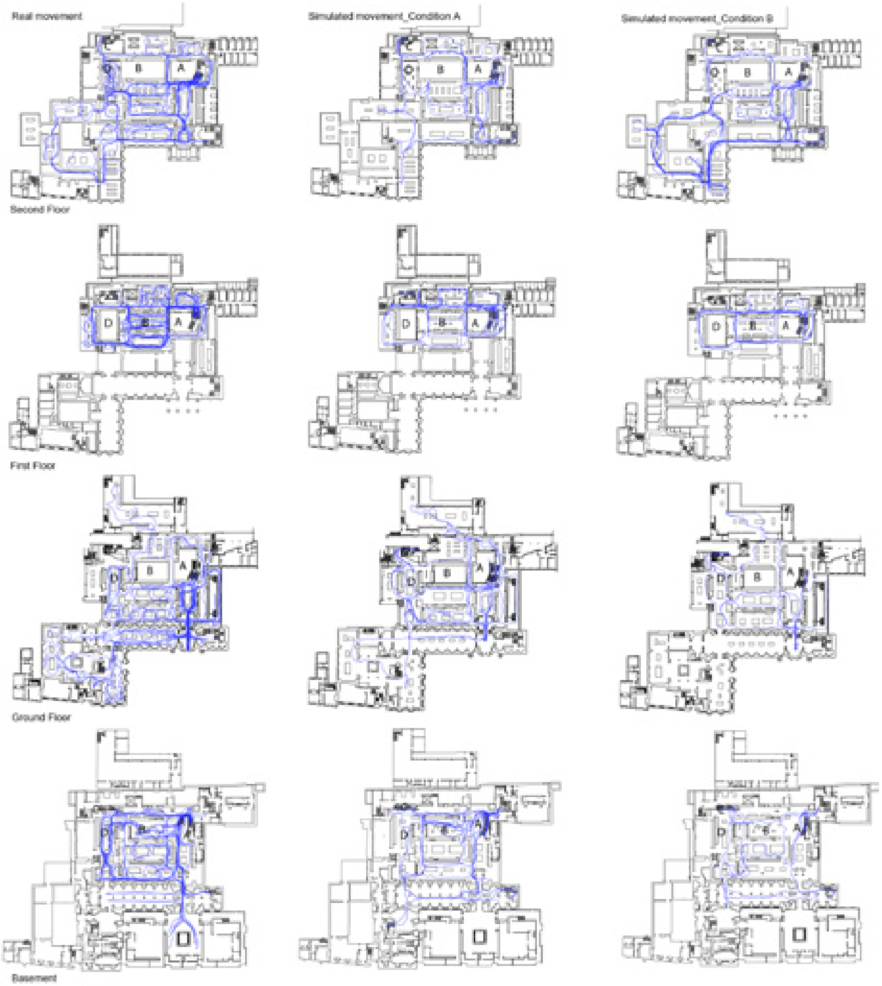
Looking more closely at the r-squared values, the ground floor (real compared to condition A), presents the lowest correlation (0.40, $p<0.01$) (Figure 4). This could be associated with the fact that people in VR are familiarizing themselves with the technology. An additional reason could be that users revisit more than once the ground floor to reach the other levels and return to the exit, in order to finish the experiment. All these factors could contribute to skewing the relationship between virtual and real movement. On the other floors, the correlations are very strong with the highest one occurring on the second level. The same factors apply when comparing real with virtual movement in Condition B, where the ground floor shows overall the lowest values (0.28) and the highest correlations are identified on the second floor (0.74, $p<0.01$) (Figure 4). The experimental procedures and subsequent comparative analysis, show that three-dimensionality is a powerful factor, associated with navigation. It is important to mention that the correlations might have been different if the virtual environments would be populated by other people and the technology had not affected participant's virtual performance through factors such as motion sickness.

The focus now shifts to the structure of the navigation paths for the separate layers of the museum. In the real Ashmolean, half of the people, upon entering the building, turn left to the Cockerell axis and half to the main axis (Figure 5) (Lazaridou and Psarra, 2015). The percentages in the virtual world A are 56% for the users choosing the Cockerell axis and 44% for the main axis. This difference is possibly associated with the presence of numerous exhibits along the Cockerell axis compared to the main axis or the fact that in the real museum the natural light is stronger, entering from the skylight of atrium A. In contrast, in Condition B the navigation paths present a different distribution as follows: the majority of the subjects (64%) move towards the Cockerell axis, 24% use the main axis and 12% turn to the right (Figure 5). There seems to be a degree of similarity between real and virtual movement in Condition A compared to Condition B, where the atria are closed off and the three-dimensional views are obscured. Moreover, from the outset, it seems as if atrium A, in Condition A, acts as a significant attractor regarding the initial route choices people make, also supporting the effect of the third dimension being significant when people enter a building. In other words, the absence of atria in Condition B directs people along the Cockerell axis. This confirms the hypothesis that in the real world and Condition A users are attracted by atrium A and three-dimensionality.

Focusing on users who follow exploration pattern 'a' (main axis towards atrium A) on the ground floor across all scenarios, it is seen that the paths in Condition A are visually more similar to the observed real movement compared to those in Condition B (Figure 5). This shows that the existence of atria on the entrance level of the museum, attracts and enhances navigation around them and also motivates users to explore its deeper parts (75%) compared to Condition B, where people concentrate in the front galleries (62%). On the other hand, the exploration pattern 'b', in Condition B, shows more similarity to the real exploration pattern 'b', than in Condition A (Figure 6). This signifies that once users choose to follow the sequential galleries, their movement is prescribed by the outline of the floor plan with the tendency towards peripheral movement, clearly shown in Condition B. In this case, the atria, do not play a significant role in navigation, since the sequential circulation structure overrides the role of the third dimension. The fact that the exploration pattern 'b' in Condition A is not so similar with the real traces supports the idea that the stage in which users encounter the atrium in their journey is an important factor. In Condition, where users reach the atria upon entering (exploration pattern 'a'), they mostly concentrate around the core of the building, compared to the latter case (exploration pattern 'b'), where the atria are introduced later and do not affect their movement significantly (Figures 5, 6).

Moving on to the two exploration patterns 'a' and 'b' on the rest of the floors, it seems that they create opposing exploratory patterns (Figures 5, 6). In Condition A, participants move mostly around the core of the building and in between the atria using the wide views and re-orientating themselves. They use the integration core of the building together with the three-dimensional views to create their own journeys. On the contrary, in Condition B, they use the peripheral galleries and the whole extent of the spatial layout to gradually increase their perceptual awareness about their spatial positioning, since they are deprived of wider views. Therefore, the absence of the third dimension drives people to the most segregated spaces, following the sequential galleries, depriving them of the information needed to make their own choices.

Next, focusing on the 'return to the entrance' task, we see that 68% of the participants in Condition A use atrium A to reach the ground floor, compared to atrium C (33%). In contrast, in Condition B, 57% use atrium A and 43% atrium C. This signifies that the existence of panoramic views in Condition A, and the centrally situated and integrated atrium A, attract almost double the number of users compared to Condition B. Atrium A clearly acts as an orientation and reference point. However, when it is closed off, it loses its strong role within the three-dimensional system and people choose whichever vertical connection they find next to their location. Atrium C, on the other hand, in Condition A, does not attract a lot of movement. In Condition B, despite not providing views, its integrated position means it is chosen by more users. Overall, three-dimensionality presents a stronger impact on navigation than the two-dimensional spatial configuration of the museum but once the third dimension is eliminated, the two-dimensional spatial configuration becomes the dominant influence on exploration.



Route choices	Main axis	Cockerell axis	Right
Real	48%	50%	2%
Condition A	44%	56%	0%
Condition B	24%	64%	12%

Figure 5 - Exploration pattern 'a' showing real and virtual traces (Conditions A and B) in the Ashmolean Museum. Paths initiate from the main axis on the ground floor and atrium A on the rest of the floors. The table shows the percentages of people based on their route decisions upon entering the environments on the ground floor.

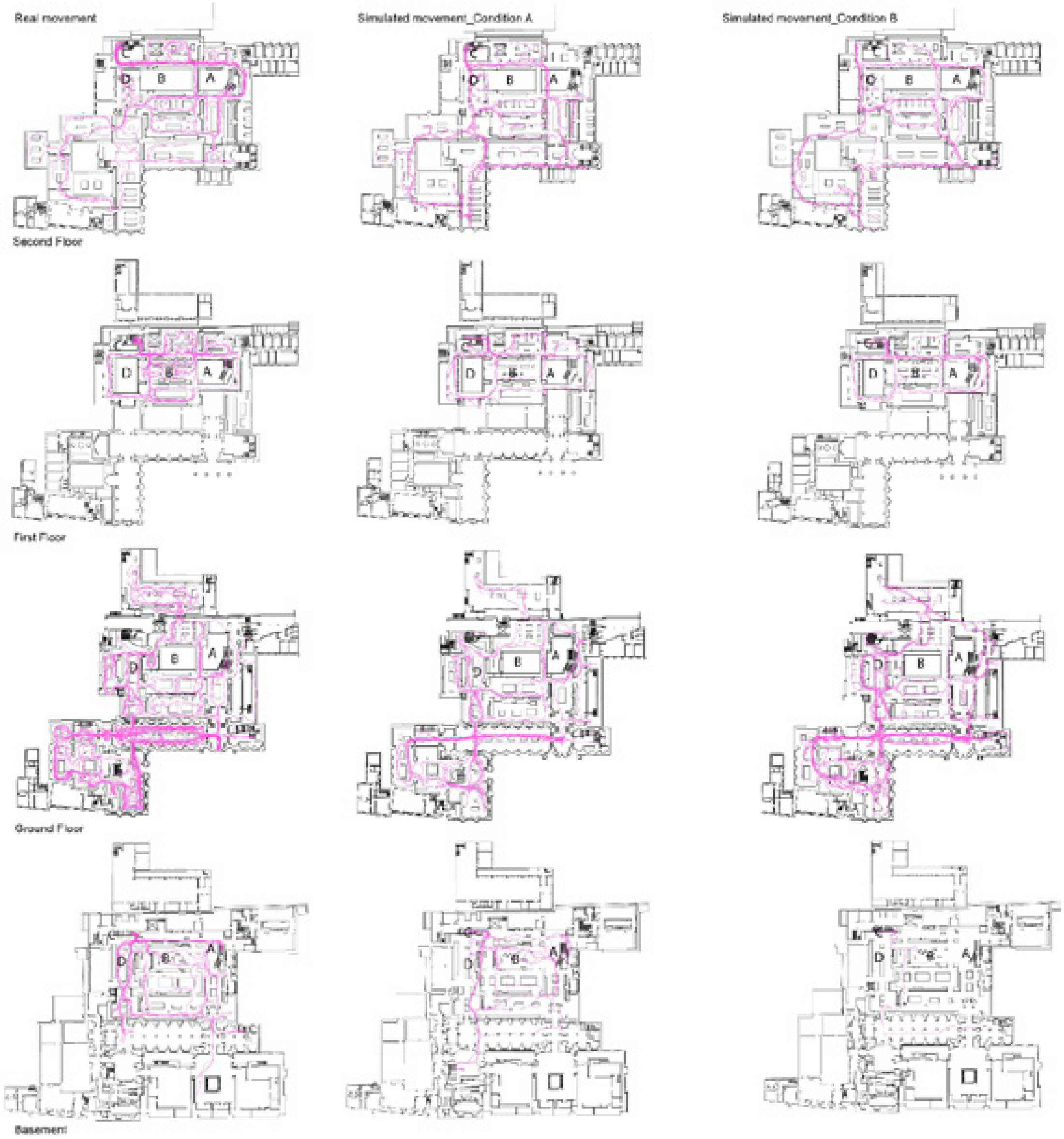


Figure 6 - Exploration pattern 'b' showing real and virtual traces (Conditions A and B) in the Ashmolean Museum. Paths initiate from the Cockerell axis on the ground floor and atrium C on the other levels.

The average rate of people changing level is higher in the real museum and in Condition A than in Condition B. On the ground floor, 60% of subjects change floor level upon reaching an atrium in Condition A compared to 46% in Condition B. In the latter scenario, where the voids are enclosed, the fact that the staircases are located in them enhances vertical circulation. Further, it is interesting to note that in the real environment, three-dimensionality affects navigation to a greater extent as visitors ascend in floor levels. On the contrary, in the virtual worlds, the effect is stronger on the ground floor and weaker on the other levels. The reason for this 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. They are also given the task to cover many spaces and they seem to proceed so as to move efficiently.

An important finding refers to the correlations between the spatial properties and the virtual paths. In terms of VGA visibility, the R^2 reaches 0.36 ($p<0.01$) on the ground floor of Condition A compared to the real environment ($R^2=0.14$, $p<0.01$) (Table 1). This could be associated with the presence of other factors in the real environment, such as the internal climate, attractions, special exhibitions, light, noise, presence of people, separately from the purely configurational characteristics. On the upper levels of Condition A, the correlations become weaker. This is explained by the fact that three-dimensionality is introduced, attracting people's movement away from the gallery spaces. Another similarity between Condition A and real paths is that VGA visibility measures correlate better with the real traces than permeability ones.

Next, the strongest correlations appear when calculating the spatial properties against the virtual paths of Condition B. In particular, VGA permeability reaches $R^2=0.47$ ($p<0.01$) on the first floor (Table 1). VGA visibility values show strong correlations on the lower levels but weaker ones on the upper floors, something in contrast to what happens in real life and the virtual Condition A. This clearly illustrates that the effect of atria and three-dimensionality seem to have a stronger impact on users' navigation than the two-dimensional configuration on its own.

Finally, when agent patterns (Turner and Penn, 2002) are correlated with the virtual paths, it is observed that the r-squared values between the agents and virtual paths are relatively weaker compared to their correlations with the real paths (Figure 8). This happens because in the virtual scenarios, exploration is three-dimensional, with continuous level changes and returning visits, which is not the case with the two-dimensional agents. However, it is clear that Condition B shows better correlation values than Condition A (Table 1). In addition, the upper levels in Condition A, present no correlations (close to zero), which can be possibly attributed to the existence of panoramic views.

Correlation R^2			
Real Ashmolean	**Agents/Traces**	**VGA perm (HH)/ Traces**	**VGA visib (HH)/Traces**
Basement	0.10 ($p<0.1$)	0.09 ($p<0.01$)	0.13 ($p<0.01$)
Ground Floor	0.41 ($p<0.01$)	0.17 ($p<0.01$)	0.14 ($p<0.01$)
First Floor	0.36 ($p<0.01$)	0.09 ($p<0.1$)	0.03 ($p<0.1$)
Second Floor	0.02 ($p<0.1$)	0.14 ($p<0.1$)	0.34 ($p<0.01$)
Condition A			
Basement	0.38 ($p<0.01$)	0.26 ($p<0.1$)	0.38 ($p<0.1$)
Ground Floor	0.06 ($p<0.1$)	0.29 ($p<0.01$)	0.36 ($p<0.01$)
First Floor	0.04 ($p<0.1$)	0.18 ($p<0.01$)	0.04 ($p<0.1$)
Second Floor	0.09 ($p<0.01$)	0.21 ($p<0.1$)	0.14 ($p<0.1$)
Condition B			
Basement	0.16 ($p<0.1$)	0.25 ($p<0.1$)	0.28 ($p<0.1$)
Ground Floor	0.06 ($p<0.1$)	0.28 ($p<0.01$)	0.47 ($p<0.01$)
First Floor	0.29 ($p<0.01$)	0.47 ($p<0.01$)	0.03 ($p<0.1$)
Second Floor	0.24 ($p<0.01$)	0.27 ($p<0.01$)	0.02 ($p<0.1$)

Table 1 - Correlations between the spatial variables and traces in the real Ashmolean and the virtual conditions.

Figure 8 - Agent-based models for the Ashmolean Museum. Red areas show high movement rates and blue ones low.
The circles signify the areas where differences are observed with real movement. 50 agents are released with standard properties (Turner and Penn, 2002): a walking pace of about 1.5ms-1, three steps to decision and a field of view of 170°.

The fact that there is a weaker correlation between simulated and human movement in Condition A and a stronger one in Condition B is a significant result. In addition, agents, as presently calculated in the Depthmap software, do not produce very high correlations and are not able to take into account all the properties that can affect human exploration.

To summarise, the existence of a significant correlation between the real paths and condition A (Figure 4) implies that VR technology can be regarded as a valuable tool in predicting movement. Moreover, the presence of other people inside the virtual worlds might have had a significant impact on the virtual explorations. However, the absence of additional virtual users may have helped participants to focus on the spatial properties of the environments. Additionally, it is interesting to notice that, although the two observation methods were different (real: on-site observations, virtual: pre-programmed script), there still seems to be a strong correspondence between the analyses. In particular, the differences, in terms of movement, in the R^2 values between the two Conditions, signify the effects of the existence or absence of atria.

Further, through the analysis of the observed and virtual paths, it can be argued that the most visited is atrium A, by virtue of its integrated position and its vistas, compared to atrium C. This finding confirms that it is not solely the integrated values of a space that attract movement, but also its three-dimensional properties. In addition, the voids enhance and attract exploratory movement but also provide global orientation. On the contrary, the absence of three-dimensional views, especially upon entering a building, direct people towards sequential routes that guide them through integrated or segregated spaces. In the first case, where visitors move towards the atria, they navigate using their own spatial thinking and global understanding, without exhaustively moving through all of the spaces in the museum. In the latter scenario, where they follow the sequential routes, their movement is directed by small scale actions and decisions that result in aggregate patterns highlighting the peripheral galleries of the building.

6. ENGAGING WITH THREE-DIMENSIONALITY

This section goes into more detail regarding users' head orientation and gaze direction as they navigate in the virtual museum. Figure 9 shows the participants' visual activity in Conditions A and B, using arrows to illustrate the direction of sight. It is interesting to notice the visual and numerical differences between the two datasets. Users, in Condition A, turn their head horizontally mostly on the platforms next to atria A, B and C, as well as at the intersection point between the Cockerell and the western axis (Figure 9C). In contrast, in Condition B, users engage more with their surroundings, with their visual activity being dispersed throughout the floor. This clearly shows that in Condition A, users orientate themselves and take their spatial decisions in fewer spaces than in Condition B, due to the existence of three-dimensionality. This is why the concentration points of gaze direction are adjacent to the voids, double-height spaces or intersections in Condition A. On the other hand, in Condition B people seem to be turning their head more frequently seeking direction and orientation (243 times in total) compared to Condition A (183 times). Condition B appears to be a more difficult environment for people to navigate since users need to constantly check their position in relation to their previous and next steps. Overall, we see that in Condition A people engage visually with their surroundings in panoramic areas and in locations where route choice decisions need to be made. In contrast, in Condition B, they look around more frequently while moving (not only at the intersections) because the nature of the environment does not provide orientation and makes decision-making more complicated.

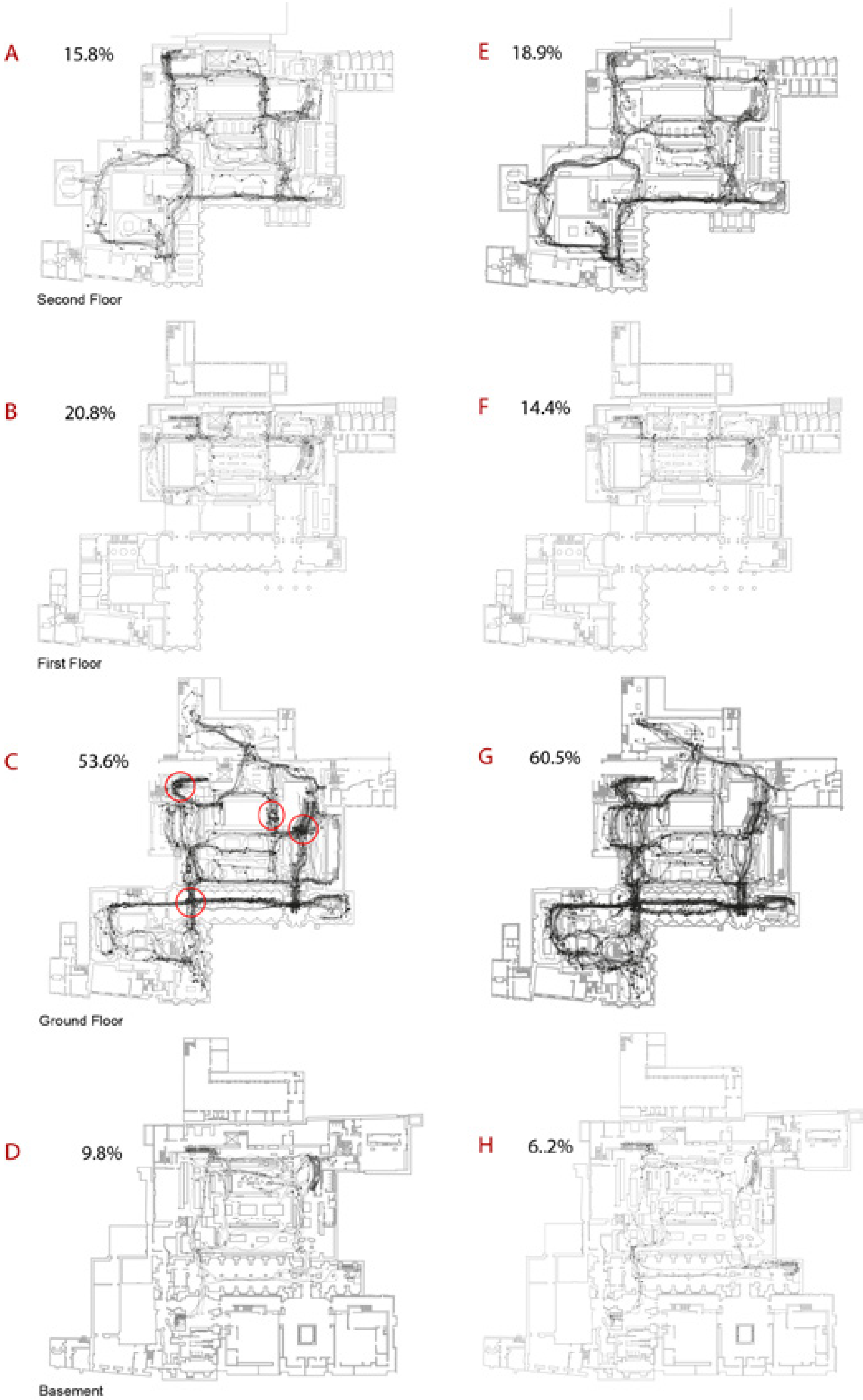


Figure 9 - Head movement (horizontal axis) in Condition A (left) and Condition B (right).

Moving a step further and looking at head movement along the vertical direction, the data indicate that subjects seem to engage with the third dimension in multiple ways using a full range of the head movement. Users in Condition A engage more with three-dimensionality compared to the ones in Condition B. Specifically, the times they look up and down in Condition A is more than double (2.44 times) compared to Condition B. The viewing points are clearly differentiated between these two worlds (Figure 10). This suggests that the more intense the radial distribution is, the more people seem to be attracted by the adjacent location and also the more time they potentially spend browsing the panoramic views.

Specifically, in Condition A, the areas next to the atria A, B, C and D show extensive browsing activity compared to Condition B, where the concentration is identified at the entrance point on the ground floor and the intersection of the Cockerell and western axis (Figure 10, circled points). This happens because in Condition A the three-dimensional views attract users around the atria. In contrast, in Condition B the views are obscured and viewers are restricted to taking route decisions at main intersections points, such as the Cockerell with the western axis. Thus, the absence of panoramic views encourages more route decisions to be made at spacious intersection points.

To sum up, a significant finding arises from the analysis which identifies the difference between the horizontal and vertical gaze direction. In particular, in Condition A, participants do not use horizontal browsing so extensively but scan the vertical dimension, unlike the subjects in Condition B, who act in the opposite way. This happens because the first environment provides a global understanding of the three-dimensional space. It further eases navigation, motivates users to admire the views, orientate themselves and plan their next steps. The latter condition guides users to a sequential layout that provides local cues with discontinuities in the visual field, resulting in users' disorientation and a need to constantly engage with the horizontal dimension in the absence of the vertical one. In other words, it seems that the intense engagement with the horizontal dimensions is an indicator of seeking orientation while navigating.

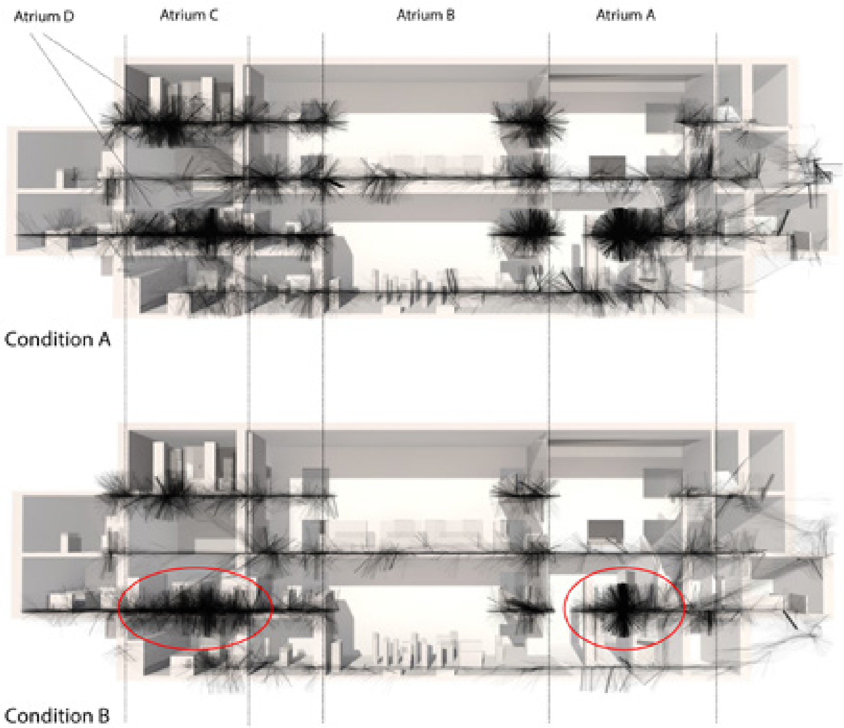


Figure 10 - Head movement of all the participants overlaid on the 3D section of the Ashmolean, using the output data from the virtual tracking.

7. CONCLUSIONS

To overview, the paper has captured the effect of atria and three-dimensionality on users' exploration in real and virtual environments. Initially, it is important to note that the navigation patterns in the real Ashmolean and in the virtual Condition A present a high degree of correlation. This shows that VR technology can be used as a competent tool to examine, evaluate and research complex environments. However, to achieve the best results, the virtual representations should be designed to simulate the target reality as closely as possible. Therefore, it seems that virtual worlds can be used to gather data, simulate real movement and predict phenomena.

Further, the atria seem to perform a dual role, being both expressive and functional in terms of navigation and spatial cognition. They allow natural light to enter the building, facilitate horizontal and vertical circulation, enhance cross-visibility, provide the potential for the creation of social interaction and act as three-dimensional orientation and reference spaces for visitors. The absence of voids impacts on navigation illustrated through the lower correlations between the real and virtual paths of Condition B compared to Condition A. The existence of atria, on the other hand, motivates visitors to explore all the spatial layers of a building. Further, the voids attract users by offering global visual cues to the surroundings. In other words, when atria are included in the design, visitors seem to be better oriented and move in more selective and critical ways. On the contrary, when the architectural design does not contain any atria, people appear more disorientated, get lost and exhaustively pass through all of the segregated spaces in the building. The outcomes show that the three-dimensional layout has a stronger influence on navigation than the two-dimensional spatial configuration.

In addition, the visual engagement with the third dimension is more intense when atria exist inside a building environment. Extended head movement on the vertical dimension illustrates the need for orientation but also attraction to the wide views from the three-dimensional voids. In contrast, the intensity of visual activity on the horizontal plane illustrates users' need for orientation and understanding of their global positioning in space. These concentration points capture the decision making areas, being at the intersection points of the galleries.

Finally, simulated movement (agent-based models) shows a stronger relationship with the navigation paths in Condition B, where the three-dimensionality is obscured ($R^2=0.29$, $p<0.01$). Thus, agent analysis can be applied on sequential layouts and provide useful information for predicting movement wherever the permeability structure of a layout is identical to the visibility. This analysis reinforces the argument regarding the significant impact of three-dimensionality on exploration in museums and overall in building environments.

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