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Additional Information

Navigation comparison between a real and a virtual museum: time-dependent differences using a head mounted display

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The validity of environmental simulations depends on their capacity to replicate responses produced in physical environments. However, very few studies validate navigation differences in immersive virtual environments, even though these can radically condition space perception and therefore alter the various evoked responses. The objective of this paper is to validate environmental simulations using 3D environments and head-mounted display devices, at behavioural level through navigation. A comparison is undertaken between the free exploration of an art exhibition in a physical museum and a simulation of the same experience. As a first perception validation, the virtual museum shows a high degree of presence. Movement patterns in both “museums” show close similarities, and present significant differences at the beginning of the exploration in terms of the percentage of area explored and the time taken to undertake the tours. Therefore, the results show there are significant time-dependent differences in navigation patterns during the first 2 minutes of the tours. Subsequently, there are no significant differences in navigation in physical and virtual museums. These findings support the use of immersive virtual environments as empirical tools in human behavioural research at navigation level.

Keywords: Virtual Reality; navigation; head-mounted display; human behaviour tracking; movement tracking; presence; immersive virtual environment; virtual real comparison

Research highlights:

- The latest generation HMDs show a high degree of presence.
- There are significant differences in navigation patterns during the first 2 minutes of a tour.
- Adaptation time need to be considered in future research.
- Training rooms need to be realistic, to avoid the “wow” effect in the main experiment.
- Results support the use of Virtual Reality and the latest HMDs as empirical tools in human behavioural research at navigation level.

1. INTRODUCTION

Environmental simulations are representations of physical environments that allow researchers to compare reactions to common concepts (Kwartler, 2005). They are particularly important when what they depict cannot be physically represented. Therefore, they are widely employed in different areas related to human behaviour. Similarly, the emergence of virtual reality has generated a wide range of possibilities, both at the scientific and the commercial level.

Virtual reality allows the development of environmental simulations in which users can perform as if they are in the real world (Alcañiz, Lozano, & Rey, 2004). These simulations have a great variety of set-ups, involving a combination of formats and supports (Mengoni, Germani, & Peruzzini, 2011). They have been progressively integrated into studies as the relevant technologies have evolved. On the one hand, among the formats - understood as the codification standard - photography and 3D environments are highlighted. Photographs, including panoramic images, provide us with non-interactive visual representations, whereas 3D environments can generate interactive representations. On the other hand, display devices - the technological devices used to visualize the formats - can be classified according to their capacity to isolate the user from physical reality (Rangaraju & Turk, 2001), also known as immersion. Immersion is defined as the objective level of fidelity that a virtual reality system provides and, while it is related to human perception, it is inherent in each technology (Slater, 2003). Thus, virtual reality can be displayed by: non-immersive systems, usually single-screen, such as desktop PCs; semi-immersive, surround-screen systems, such as the cave automatic virtual environment (CAVE); and fully-immersive systems, such as the head-mounted display (HMD).

The environments displayed through immersive devices are called immersive virtual environments (IVE) (Blascovich et al., 2002). Today, the tendency is to use virtual reality environments through immersive displays. Their synergy offers a higher sense of presence (Sanchez-Vives & Slater, 2005), understood as the illusion of 'being there' (Steuer, 1992). While these set-ups were, in the past, difficult to implement, they are now much more accessible (Parsons, 2015) and have improved performance. Furthermore, the progress in virtual reality set-ups has led researchers to involve the human body in simulation experiences: introducing full embodiment in a virtual environment, understood as the sense of using our body coherently as we do in the real world (Dourish, 1999), enhances sense of presence by the incorporation of natural interactions.

Virtual reality is being increasingly used in the area of natural phenomena and social interaction simulation, due to its ability to activate brain mechanisms that are similar to those in real life (Alcañiz, Rey, Tembl, & Parkhutik, 2009). Since VR allows the measurement of performance in real-time, it has become an important investigative tool in the field of human behaviour research. Specifically, VR is widely employed in psychological assessment (Freeman et al., 2017), medical treatment (Dascal et al., 2017), education (Jensen & Konradsen, 2017; Babu, Krishna, & Bhavani, 2018), emotion recognition (Marín-Morales et al., 2018) and architecture (Portman, Natapov, & Fisher-Gewirtzman, 2015), among other areas.

The usefulness of simulation for human behaviour research has been analysed through the concept of validity: the capacity to evoke a response from the user in a simulated environment similar to one that might be evoked by a physical environment (Rohrmann & Bishop, 2002). Comparisons between physical spaces and their simulations through 3D IVEs have been made at different levels. At a physiological level it is found that 3D IVEs evoke responses more similar to those elicited by physical environments than formats with lower interactivity, although at the psychological level the validity decreases when compared to other formats, due to its lower realism (Higuera-Trujillo, López-Tarruella, & Llinares, 2017). In addition, measured by psychological response, a relation is found between sense of presence and the immersive capacity of HMDs (Baños et al., 2004) and the navigation metaphor (Usoh et al. 1999). Other studies have carried out comparisons between real and virtual spaces, analysing user performance in sets of everyday office-related activities (e.g. reading texts and identifying objects in an office environment) (Heydarian et al., 2015), physiological responses in different thermal conditions (Yeom, Choi, & Zhu, 2017), subjective perception of daylight spaces (Chamilothori, Wienold, & Andersen, 2018) and orienteering tasks (Kimura et al., 2017).

Navigation encompasses travel and wayfinding components (LaViola, Kruijff, McMahan, Bowman, & Poupyrev, 2017). On the one hand, the travel function is related to the task of moving from one point to another and, therefore, to the metaphors employed for executing displacements. On the other hand, wayfinding is the cognitive process of establishing a route or path from an origin to a destination.

Regarding the travel component, interaction and navigation techniques are especially important aspects. They may, even, influence sense of presence (Slater & Usoh, 1994; Usoh et al., 1999). Different metaphors are discussed in terms of their efficiency in navigation. The benefits of full free-physical motion are frequently

emphasized, although there is no consensus as to which is the standard method of navigation (Lee, Ahn, & Hwang, 2018). However, it is suggested that performing only body rotations might be useful: users adopt other strategies to increase the surface that they cover (Riecke et al., 2010). Other metaphors, such as those based on head motions to indicate forward movements, have also been studied with relative success (Tregillus, Al Zayer, & Folmer, 2017). In addition, there seems to be consensus that the exclusive use of joysticks is not the most efficient navigation metaphor (Wilson, Nguyen, Harris, & Williams, 2014), despite its familiarity. However, in terms of their ability to generate a user navigation experience similar to that of a physical space, no research intensively compares different metaphors and navigation devices in a controlled environment.

The wayfinding component is fundamental to the user's performance. This applies equally to virtual and physical environments, as the knowledge acquired in both has a similar structure (Ruddle, Payne, & Jones, 1997). Hence, for example, wayfinding component analysis has been used successfully for firefighting training (Bliss, Tidwell, & Guest, 1997). Several studies compare virtual and physical environments, generally concluding that the virtual offers worse performance than the physical (Richardson, Montello, & Hegarty, 1999; van der Ham, Faber, Venselaar, van Kreveld, & Löffler, 2015). Some authors claim that these differences can be attributed to a lack of user involvement caused by technical limitations (Lessels & Ruddle, 2005), fundamentally of the display (as field of view, or photorealism) and navigation (as metaphors, or degrees of freedom) systems. These studies focus on non-immersive or semi-immersive systems. However, very few studies compare physical space and its virtualization displayed through immersive systems. Taking into account the growing use of IVEs, and the fact that HMDs offer better performance - in terms of speed of navigation - than desktop screens (Ruddle, Payne, & Jones, 1999), there is a clear need to make this comparison using the most modern HMDs.

The present work addresses these limitations. Specifically, the objective is to validate environmental simulations by means of 3D IVEs at a navigation level. The research question to be answered is: are there differences between navigation in a physical space and its virtualization using a 3D IVE and a latest generation HMD? A comparative study was conducted of a free exploration of an art exhibition in an actual museum and a virtual museum simulated by means of an HTC Vive. The results may be of interest to researchers and content developers and are applicable to different fields.

2. MATERIAL AND METHODS

2.1 Participants

A homogeneous group of 60 healthy subjects (age 28.9 ± 5.44 , 40% men, 60% women) were recruited. They all received financial compensation. The criteria were as follows:

- (i) Age between 20 and 40
- (ii) Spanish nationality
- (iii) Not having formal, or informal, training in fine arts
- (iv) Not having previous experience of HMDs
- (v) Not having previously visited this particular exhibition
- (vi) Having normal vision, or corrected to normal with contact lenses

Two questionnaires were included to ensure that the subjects had healthy mental conditions and homogeneous emotional responses. First, the subjects were analysed by the Patient Health Questionnaire (PHQ) (Kroenke, Spitzer, & Williams, 2001). Only subjects with a value inferior to 5 were included to avoid including individuals in states of depression. Second, a selection of IAPS images (Lang, Bradley, & Cuthbert, 1997) were evaluated by the participants using the Self-Assessment Manikin (SAM) (Bradley & Lang, 1994). The images had a range of 3.41 to 7.24 in arousal and of 1.29 to 8.17 in valence (selected images: 7234, 5201, 9290, 1463, 9181, 8380, 3102, 4652). The participants' self-assessments were normalized by means of a z-score using the means and deviation published in the IAPS. Participants with evaluations outside of the range -2.58 and 2.58 ($\alpha=0.005$) were excluded since they were considered outliers.

2.2 Physical museum

During the first phase of the study, 30 subjects visited an actual museum to perform the test. The Institut Valencià d'Art Modern (IVAM) offered its facilities for the study.

The exhibition "Départ-Arrivée" by Christian Boltanski was selected due to its high emotional content, since its setting is the Nazi holocaust and because it was spacious enough to allow users to freely navigate. It consisted of five rooms with an approximate total floor surface area of 750 m² (Figure 1). Each room is considered to be a

single piece of art. In addition, the last room contained three art pieces that could be analysed independently. Furthermore, the rooms presented information boards with the artist's notes on the works. Finally, in Room 3 there was a path laid out from which subjects could not deviate.

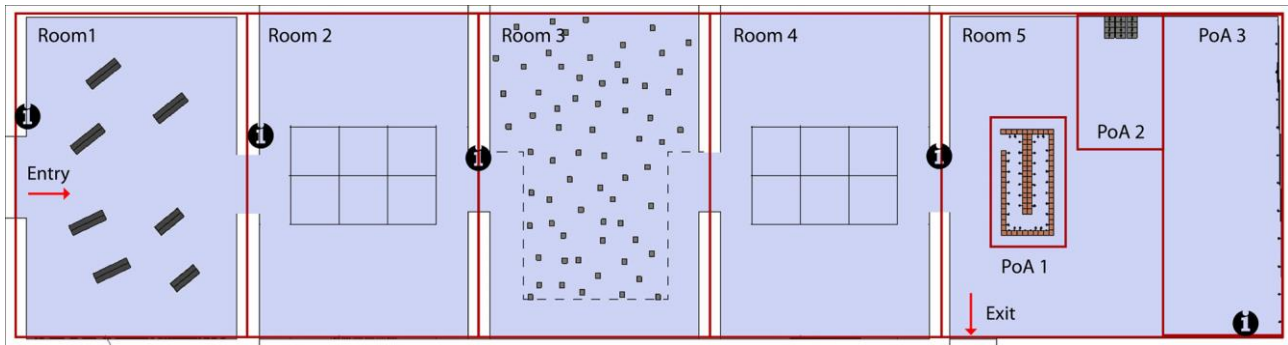


Figure 1: Plan of the art exhibition. Circles with an “i” represent the artwork information boards. In room 3, the dashed line represents a limit that could not be crossed by the subjects.

The subjects were told, before starting the experiment, that they could freely explore the first four rooms. In the last room, while they also could explore it freely, they had also to view, in detail, the three pieces of art in the room. The researcher waited for the subject at the exhibition exit, allowing the subjects to explore the space without any external influence.

A GoPro camera was used to record the subjects' navigation. The subjects carried this attached to their chests by means of a harness (Figure 2).



Figure 2: Example of a subject in the physical museum.

2.3 Virtual museum

During the second phase of the study the museum was virtualized using a 3D scenario. For this we used the Unity 5.1 game engine (www.unity3d.com). In order to achieve a scenario with maximum realism, we imported a three-dimensional copy of the exhibition created by Rhinoceros v5.0 and textures partially derived from the physical environment. This process required the exhaustive and methodical drawing and photographing of the whole exhibition. A team of architects visited the physical exhibition and carried out a validation of virtualization at a general level, and of the level of lighting and texturing. Virtualization was considered complete after the appropriate changes. Figure 3 shows photographs and screenshots of the virtual environment.

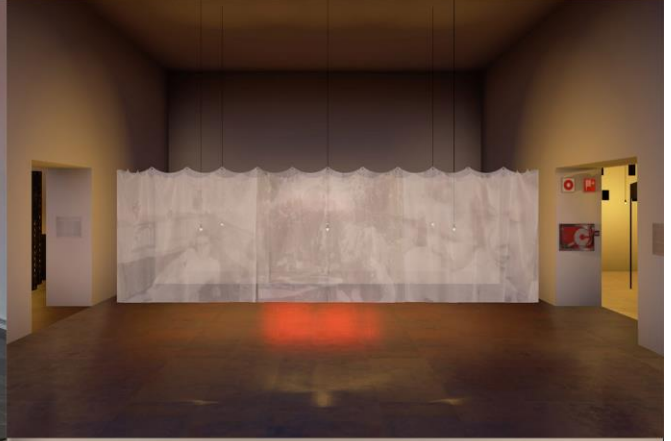


Figure 3: Comparison between a photograph of the physical museum (left) and a screenshot of the virtual museum (right). From top to bottom, Room 1, Room 2, Room 3 and Room 5.

For the simulation of the 3D VR, we compiled the scenario for HTC Vive (www.vive.com), which enabled us to carry out visual and displacement simulations. Visualization was conducted by means of an HMD with 2160x1200 pixels (1080x1200 per eye), and a field of view of 110 degrees working at 90Hz refresh rate. On the other hand, we conducted the displacements by means of a tracking technology made up of two controllers and two base stations that, together, enabled the subject to interact with the environment and physically move within an area of a 2x2 metres. Specifically, the metaphor used was the teleport navigation metaphor incorporated into the HTC Vive with a maximum teleportation radio of 2.5 metres from the subject. This was selected because we hypothesize that it will allow us to achieve pseudo-naturalistic navigation. The equipment was connected to the research computer (Predator G6, www.acer.com) by means of a DisplayPort 1.2 and USB 3.0 and ran smoothly and without interruption.

After the environmental simulation of the art museum had been created, the study was replicated using the 3D IVE with the second group of 30 subjects in a lab environment. Figure 4 shows a subject exploring the virtual museum.



Figure 4: Example of a subject viewing the virtual museum.

Before starting the experiment, the subjects carried out several tasks to adapt themselves to the HMD device and to the navigation metaphors, in a neutral scenario, without textures. The researcher ensured that the subject adapted correctly and navigated fluently. The subjects could stay in this scenario for as long as they wanted, until they considered that they could use the device without difficulty. During this period, the researcher addressed any doubts raised by the subjects about the HMD device, given that they had no previous HMD experience. Figure 5 shows a screenshot of a training environment.

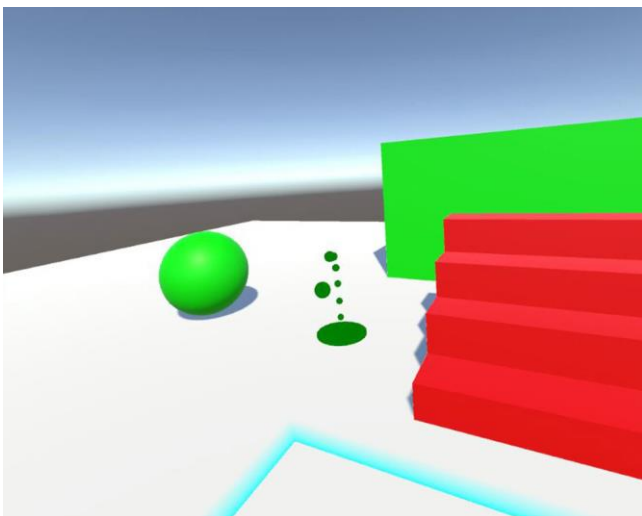


Figure 5: Screenshot of the training environment.

After the training, the researcher gave the subjects the same instructions as were given to the subjects who had visited the physical museum. During the virtual experiment, the researcher remained in an adjoining room. Finally, the researcher was able to note through the monitor when the subject arrived at the exit of the "museum" and then removed the HMD device. Following the test, the subject had to answer a presence questionnaire, the "SUS questionnaire" (Martin Usoh, Catena, Arman, & Slater, 2000). This consists of six items assessed from 1 to 7 using a Likert scale to measure three aspects of presence:

- (i) The experience of being inside the simulation.
- (ii) The consideration of the simulation as the dominant reality.
- (iii) The memory of the simulation as a place.

2.4 Signal synchronization

Regarding navigation in the physical museum, software was developed using the "Microsoft Virtual Studio" in C++ language to synchronize the data. The software simultaneously shows two items: a video recording of the subjects' exploration of the exhibition and a plan of the exhibition. It includes two buttons that can advance and rewind the video with 1-second jumps. In addition, it allows the position of the subjects to be manually entered into the plan, using the video as a reference. The researcher reviewed all the videos, positioning the subjects in the plans at 1-second intervals. Finally, the navigation path was saved to a file with the route sampled every second.

Regarding navigation in the virtual museum, a script in Unity was developed which recorded the subjects' positions at a frequency of 7Hz while they were exploring the scenario and exported them to a csv file at the end of the test. Finally, the recorded navigation path was resampled to the same frequency as the path generated in the physical space (1 Hz).

2.5 Spatial segmentation and analysis

The analysis of the subjects' navigation was based on the framework developed by Marín-Morales et al. (Marín-Morales, Torrecilla, Guixeres, & Llinares, 2017). This proposes the segmentation of space into Areas of Interest (AOIs) on which several indicators are calculated to characterize navigation. The exhibition is comprised of twenty-three AOIs. The first five AOIs are defined by the area of the five rooms. Moreover, each room was divided into several internal AOIs. Rooms 1, 2 and 4 are divided into four symmetrical AOIs. Room 3 is divided into three AOIs covering the walking area. Room 5 is divided into three AOIs, each of them including a specific piece of art. The analysis was carried out based on three items: the heatmaps, the percentage of area explored and the length of time of the visits.

Heatmaps were created using every point of the subjects' trajectories at 1 Hz. Subsequently, a radius of 0.75 m was applied to each position, defining that each subject's presence spans a circle of 1.5m in diameter. Considering that heatmaps are usually relative to themselves, i.e. they adapt the colours to the maximum and minimum values that they represent in each case, both heatmaps were constructed according to the same linear representation scale, allowing them to be comparable between themselves. The highest valued 5% of the pixels were dismissed and were saturated in red to increase the sensitivity of the heatmap. On the other hand, we calculated the percentage of area explored in each AOI by each user, considering that the area explored is calculated with the centroids of the subject's navigation points with a radius of 0.75 metres.

Regarding the length of the visits, a visit is defined as the period of time from when a subject enters an AOI to the moment he or she leaves it. In particular, the variable being analysed is the length of time of the main visit to each of the AOIs, defined as that visit with the longest duration in the case that an AOI was visited more than once by the same subject. Processing assured that the variable included the main visit to the room or piece of art: if there were less than 15 seconds between two visits to the same AOI, the visits were put together and considered as just one visit.

3. RESULTS

3.1 Self-assessment: presence and cybersickness

Table 1 shows the results of presence provided by the SUS questionnaire. Two items are between 6 and 7: "I had a sense of 'being there' in the museum space" and "During the experience I often thought that I was really in the museum space". Another two items are between 5.50 and 6: "There were times during the experience when the museum space was the reality for me" and "During the experience you felt you were in the museum

space". Finally, the two remaining items are below 5. The total average of the set of items is 5.47 out of 7 so the level of presence of the simulation is high. The subjects did not report any level of cybersickness.

Question	Score
1. I had a sense of "being there" in the museum space.	6.17 (0.95)
2. There were times during the experience when the museum space was the reality for me.	5.86 (0.95)
3. The museum space seems to me to be like somewhere that I visited before	4.87 (1.91)
4. During the experience you felt you were in the museum space	5.87 (1.17)
5. I think of the museum space as a place similar to other places that I've been today	3.93 (2.26)
6. During the experience I often thought that I was really in the museum space	6.13 (0.94)

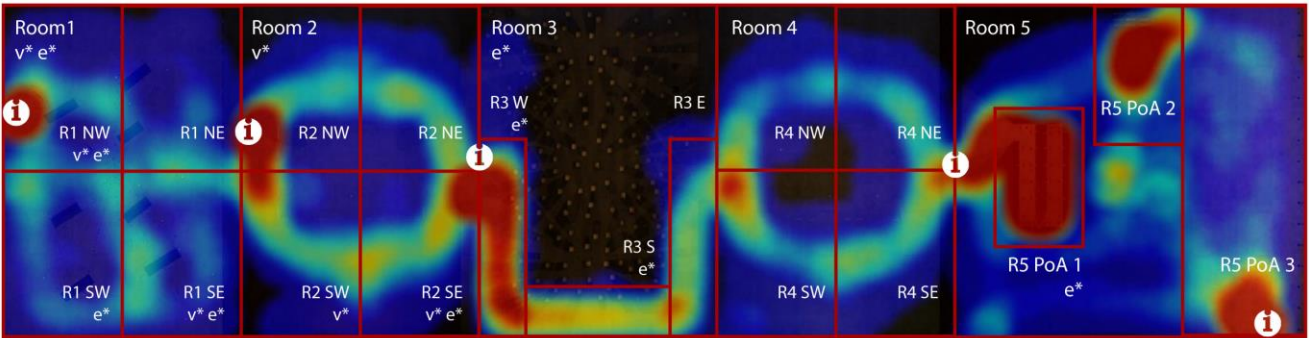
Table 1: Results of presence (SUS Questionnaire). The results are presented using the mean and the standard deviation.

3.2 Heatmaps

Figure 6 shows the heatmaps of the trajectories in the physical and virtual museums. Carrying out a descriptive analysis room by room, it is observed that:

- (i) In Room 1, the exploration is more dispersed in the physical museum. In addition, the participants are very focused on the information board in the physical museum.
- (ii) In Room 2, the trajectories are similar. However, taking into account that the natural path is that presented in the physical museum, the subjects' trajectories deviated slightly from these natural paths in the virtual museum, being a bit more dispersed. Similarly, the information board was scarcely visited in the virtual museum.
- (iii) In Room 3, the trajectories are very similar and there are no differences, except that some subjects ignored to a small extent the limitations set by the exhibition organizers.
- (iv) In Room 4, there are no differences among the trajectories, except for the same effect mentioned for Room 2.
- (v) In Room 5, there are no differences, except for the trajectory relevant to piece of art 3, where the subjects notably stopped at the information board in the physical museum, whereas the trajectories were much more dispersed in the virtual museum. It is noteworthy that, both in the physical and the virtual museum, a light spot can be seen in the middle of the room, caused by the subjects who visualised the room from its central point.

Heatmap of physical museum



Heatmap of virtual museum

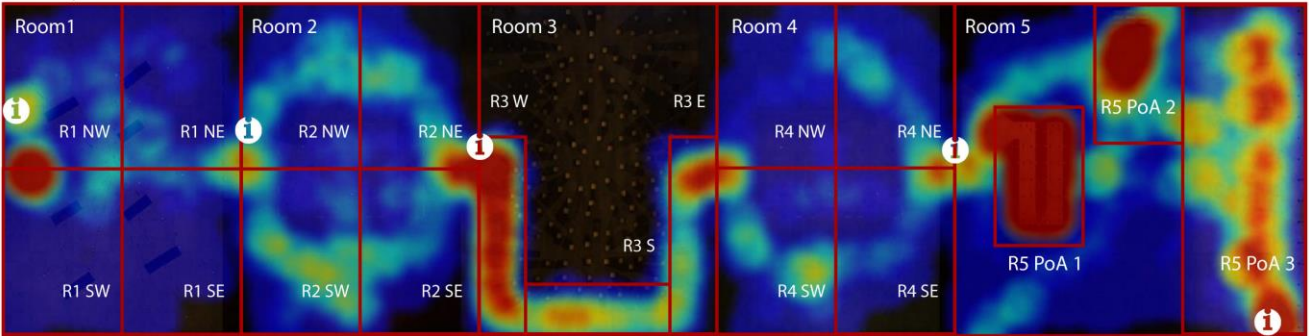


Figure 6: Heatmaps of the physical museum (top) and the virtual museum (bottom). They include the names and positions of the AOIs, and the positions of the information boards, indicated by an “i”. Below the name of the AOI, v* indicates significant differences in visit time and e* significant differences in percentage of area explored with $p < 0.05$ in each AOI. The indicators are included in the heatmap condition with major value in each case.

3.3 Length of visit time and percentage of area explored

Figure 7 shows the length of time of the main visits and the percentage of area explored in each room in the physical and virtual museums, using mean and standard deviations. Due to the Gaussianity of data ($p > 0.05$ from Shapiro-Wilk test with null hypothesis of having a Gaussian sample), a T-Test was applied. Regarding the visit times, only in Room 1 (p -value=0.00) and Room 2 (p -value=0.03) were there significant differences, subjects staying less time in the virtual museum. The percentage of area explored is higher in the physical museum for all rooms, significant differences being observed in Room 1 (p -value=0.00) and Room 3 (p -value=0.00).

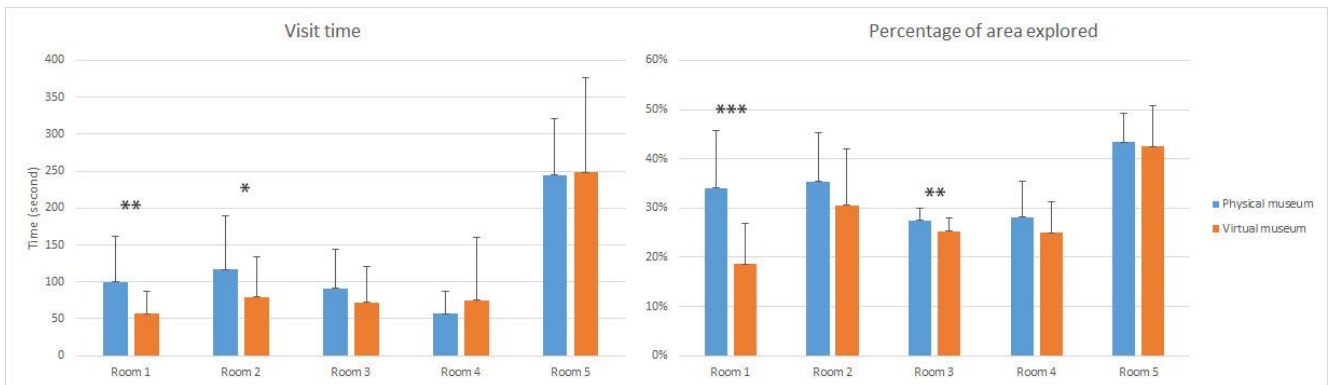


Figure 7: Representation of timings for the main visit and the percentage of area explored for each AOI. The bars represent the average and the lines represent the standard deviation. (* indicates significant differences with $p < 0.05$, ** indicates significant differences with $p < 0.01$ and *** indicates significant differences with $p < 0.001$).

Table 2 shows the visit time and the percentage of the area explored of each internal AOI and the difference between both conditions. Due to the Gaussianity of data ($p > 0.05$ from Shapiro-Wilk test with null hypothesis of having a Gaussian sample), a T-Test was applied. Considering the visit time, the main differences were found in

Room 1 (R1 NW and R1 SE) and Room 2 (R2 SW and R2 SE). The percentages of area explored were different in Room 1 (R1 NW, R1 SW and R1 SE), Room 2 (R2 SE), Room 3 (R3 W and R3 S) and Room 5 (R5 PoA 1).

Room	AOI	Visit time				Percentage of area explored			
		Physical museum	Virtual museum	Difference	pvalue	Physical museum	Virtual museum	Difference	pvalue
Room 1	R1 NW	51.93 (56.71)	20.51 (18.89)	+31.43	0.007 (**)	31.83% (4.51)	27.24% (4.27)	+4.59%	0.000 (***)
	R1 SW	25.10 (37.29)	22.42 (29.15)	+2.68	0.562	32.12% (19.03)	13.64% (11.81)	+18.48%	0.000 (***)
	R1 NE	32.17 (54.53)	17.84 (18.12)	+14.33	0.906	31.28% (18.78)	24.62% (14.89)	+6.66%	0.147
	R1 SE	45.63 (56.76)	8.74 (20.17)	+36.90	0.000 (***)	39.23% (21.95)	14.09% (13.46)	+25.14%	0.000 (***)
Room 2	R2 NW	54.23 (49.73)	37.80 (55.63)	+16.44	0.077	32.81% (15.22)	26.37% (20.32)	+6.44%	0.185
	R2 SW	69.17 (67.84)	30.20 (39.86)	+38.97	0.011 (*)	35.98% (14.59)	33.80% (20.52)	+2.17%	0.650
	R2 NE	25.57 (29.10)	33.07 (50.15)	-7.51	0.691	33.63% (14.25)	30.35% (13.90)	+3.27%	0.107
	R2 SE	71.07 (55.00)	27.65 (38.33)	+43.42	0.001 (***)	39.34% (12.19)	31.94% (13.37)	+7.40%	0.035 (*)
Room 3	R3 W	62.13 (51.61)	43.07 (48.41)	+19.06	0.118	81.70% (5.53)	74.15% (10.08)	+7.55%	0.001 (***)
	R3 S	13.40 (7.86)	14.60 (11.54)	-1.20	0.644	78.63% (4.70)	74.55% (8.65)	+4.08%	0.032 (*)
	R3 E	13.57 (6.44)	17.19 (7.19)	-3.62	0.052	71.41% (9.07)	69.27% (8.42)	+2.14%	0.365
Room 4	R4 NW	15.07 (18.88)	12.25 (20.00)	+2.82	0.229	24.55% (17.07)	19.08% (15.17)	+5.47%	0.210
	R4 SW	27.00 (30.51)	17.68 (14.70)	+9.32	0.674	33.95% (16.55)	29.31% (15.29)	+4.64%	0.281
	R4 NE	14.60 (18.04)	16.34 (14.10)	-1.74	0.686	24.19% (16.91)	25.80% (15.46)	-1.61%	0.952
	R4 SE	26.60 (26.41)	37.39 (87.28)	-10.79	0.416	30.36% (12.99)	25.44% (9.62)	+4.91%	0.114
Room 5	R5 PoA 1	76.13 (32.89)	78.44 (51.58)	-2.31	0.839	99.98% (0.06)	94.87% (18.55)	+5.10%	0.007 (**)
	R5 PoA 2	48.57 (44.62)	71.93 (96.36)	-23.36	0.840	63.03% (12.10)	57.40% (11.20)	+5.63%	0.076
	R5 PoA 3	112.90 (62.77)	115.73 (95.35)	-2.83	0.894	43.53% (11.47)	40.64% (13.23)	+2.90%	0.386

Table 2: Results of the visit time and percentage of area explored in each internal AOI. The results are presented using the mean and the standard deviation, the difference between both conditions and the p-value of the T-Test.

4. DISCUSSION

The aim of this study is to validate environmental simulations made by means of 3D IVEs and a latest generation HMD, at presence and navigation levels. The results can be discussed on four levels: i) level of presence and cybersickness, ii) differences in navigation, iii) methodological analysis and iv) comparison with previous works.

Regarding sense of presence, an overall average of 5.47 (out of 7) was shown by the SUS questionnaire. It reached more than 6 for the questions “I had a sense of “being there” in the museum space” and “During the experience I often thought that I was really in the museum space”. The results are considered to be high, taking into account the previous results reported by studies using similar technologies (Sas & O’Hare, 2003). In addition, since no subject reported any cybersickness, the self-assessment supports the use of the present set-up at a perception level.

With regard to navigation, we analysed trajectories and the lengths of visits to AOIs. The heatmaps show similar navigation patterns in the physical and the virtual museums. Room 1 shows the biggest differences between the exploration and the heatmaps, with 15.40% more area being explored in the physical environment. The heatmaps do not show the same pattern. Moreover, AOIs R1 NW, R1 SW and R1 SE present significant differences. These differences may be because, in the first room, the subject is still adapting to the IVE. The second room shows no significant differences at either the exploration level or with the path patterns in the heatmap, except for AOI R2SE. This room has a central object that tends to be avoided (Figures 1 and 3). In the physical museum, the subjects walk around this object, forming a clear rectangle in their trajectories. In the virtual museum, they tend to do the same, but not so markedly. There are subtle differences in patterns when the subjects try to avoid obstacles. Room 3 shows a similar pattern. Nevertheless, there are significant differences in the percentages of areas explored, in both the general room and in the internal AOIs (R3 W and R3 S). These differences could be

due to the navigation metaphor used. The teleport metaphor, which allows the user to perform “jumps” of a maximum of 2.5 metres, decreases the percentage of area explored when the subjects walk along a narrow aisle. This suggests that the navigation is less naturalistic in narrow environments. There are no significant differences among the patterns in Room 4, not even in the area explored percentage. No significant differences were observed in the last room in the heatmap patterns at the exploration or trajectory levels. Moreover, it was noted that the same pattern is seen in Figure 5 for the pieces of art, in the central point of the room and at the exit from the exhibition. For piece of art 1 (R5 PoA 1), we find significant differences, although, in both conditions, the percentage of area explored is more than 90%, so this does not represent a substantial difference. Moreover, this effect is similar to that observed in Room 3, where the percentage of area explored decreased, being in a narrow aisle, as the piece of art is a labyrinth. For piece of art 2, there are no differences. For piece of art 3, there are no significant differences in the exploration, but a more dispersed pattern is detected in the heatmap. Therefore, in terms of exploration, the major difference is observed in Room 1. In addition, differences were found for all the information boards. Current HMD technologies are limited for reading medium or small texts. This problem might be resolved by an increase in the resolution of the HMD systems.

With regard to the lengths of the visits, there were significant differences only in Room 1 (p -value=0.00) and Room 2 (p -value=0.03), including in both cases two internal AOs (R1 NW, R1 SE, R2 SW and R2 SE). Visits to both rooms in the virtual museum were considerably shorter than for the physical museum. The rest of the rooms do not present significant differences. Thus, taking the visual analysis patterns of the heatmaps, the percentage of area explored and the length of the visits, if we exclude the effect of the narrow aisle in Room 3 and R5 PoA1, the environment shows time-dependent differences. Consequently, and despite the implementation of a training phase which used a different scenario, it is necessary to allow a period of adaptation in the actual museum scenario until navigation behaviours do not show significant differences to those in the space that it simulates. In this study, the adaptation period was approximately 2 minutes, which is the sum of the average length of visits to Room 1 and Room 2 as shown in Figure 7. This might be explained by the fact that the training room is a non-realistic environment, since it presents abstract objects without textures (Figure 5). When the subject enters the virtual museum (Figure 3), he/she is affected by the “wow” effect caused by the realism of the VR, and thus needs some time to start to behave without displaying significant differences to the real museum. In future research, we suggest that more realistic training rooms, with textures and lighting similar to the simulated environment, should be used, to try to avoid the “wow” effect. However, it must be borne in mind that these results come from subjects with no prior experience of HMDs. In the future, when more of the population have wider exposure to these devices, this adaptation period will probably be reduced or even be unnecessary.

At a methodological level, we make a comparison using a HTC Vive, which gives good performance in terms of working area, accuracy and jitter in a room-sized environment for serious games, rehabilitation and health-related applications (Borrego, Latorre, Alcañiz, & Llorens, 2018). The role that recently developed low-cost VR devices can play in scientific research is thoroughly analysed by Cipresso, Giglioli, Raya, & Riva, (2018), who argue that they may be the next significant stepping stones in technological innovation. Therefore, as it is likely that these devices will be widely used in next years, there is an urgent need to validate them. Regarding the metaphor, some recent reviews analyse the role of the classic navigation metaphors in the new era of VR (Boletsis, 2017; Nilsson, Serafin, Steinicke, & Nordahl, 2018), dividing them into three main categories: repositioning systems, locomotion based on proxy gestures and redirected walking. There is consensus that redirected walking is the most natural way to simulate walking. However, there is also consensus that travel techniques must be developed to mimic better the actual experience of walking without requiring a physical space the same size as the virtual environment; this is the weakest point of redirect walking, as it requires large physical spaces. In the present work we suggest the use of repositioning systems, in particular teleport metaphors with a limit of 2.5 metres radius and a movement area of 2x2 metres, to provide pseudo-naturalistic walking. This set-up provides a low cost framework that requires only a small room with two base stations, which are included in the basic HTC Vive pack. The results support the use of this set-up, but future researches should compare this with other navigation metaphors, and also analyse which value of radius teleport limitation better simulates walking. In particular, the reduction of the teleport radius might provide more realistic walking by reducing the large “jumps”, but it might also reduce travel performance. Some research uses a teleport without restriction to enhance task performance and usability (LaViola et al., 2017), but this probably reduces the similarities with natural walking. The environment used in the research is chosen to analyse the travel component of the navigation, thus excluding the wayfinding component. Thus, we use a large environment (750 m²), which allows the performance of very different types of travel, but at the same time imposes an obligatory sequence for the room visits, from 1 to 5, thereby excluding the possible influence of subjects taking different routes on the travel component results. The analysis of the wayfinding process using the present set-up should in the future be undertaken in other environments which allow different routes to be taken from origin to destination.

Much previous research compares navigation between real-world and virtual reality using non-immersive and semi-immersive devices. Richardson et al., (1999) perform a navigation-performance task on a large screen; van

der Ham et al., (2015) analyse a route memory task on a computer screen; and Claessen, Visser-Meily, De Rooij, Postma, & Van Der Ham, (2016) analyse the wayfinding of chronic stroke patients using videos on a screen. Moreover, the vast majority of the comparisons are focused on the wayfinding component of the navigation, not the travel component. The few researches that use HMDs analyse navigation tasks in small spaces from an orientation and task-goal perspective. Kimura et al., (2017) perform a comparison of orientation-tasks using a HMD, and demonstrate that participants in a VR room show less facility with spatial geometry. Lessels & Ruddle, (2005) analyse a searching-task performance using an HMD and suggest that visually photorealistic environments allow navigation to take place almost as efficiently as in a real-world setting. Therefore, previous comparisons between real and virtual environments have the following limitations: i) they do not analyse the new generation of HMDs, ii) they focus on the wayfinding component of navigation, and iii) they use the goal-task approach. This present work aims to contribute to the knowledge in the field by addressing these limitations, using the new generation of HMDs, which can change the paradigm of the use of VR in research, and by analysing the travel component in a free exploration of a real-world environment and task, visiting a museum.

5. CONCLUSIONS

The virtual museum shows a high degree of sense of presence. This outcome supports the use of 3D IVEs with devices, such as HTC Vive, at the perception level and, particularly, in environments with a high emotional content, such as museums. In terms of navigation, the physical museum was explored more, although there are significant differences only in Room 1. The trajectory patterns shown by the heatmaps are very similar, although there were differences with the information boards since their medium and small sized lettering is still not easily read in HMDs. Regarding the length of the visits, the first 2 rooms show significant differences. There are significant time-dependent differences in the navigation during the first 2 minutes of the experiment, even though there was a training room. We advise that future studies using the current set-up with subjects with no experience of HMDs should include an initial adaptation period and use realistic training environments. These conclusions support the use of environmental simulations by means of 3D IVEs and HMDs as empirical tools to study human behaviour at navigation level and raise interesting questions for future commercial and research studies.

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