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Architectonic Design Supported by Visual Environmental Simulation—A Comparison of Displays and Formats

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Abstract: Visual environmental simulations are fundamental in understanding the relationship between the built environment and psychological perception. The remarkable evolution of virtual immersion displays over recent years has provided a series of advantages to the architectural discipline, one of which is that non-specialists now have the potential to better understand architectural spaces. This work aimed to analyse the adequacy of the main displays and formats currently used in environmental simulations. As the objective was twofold, two experimental studies were carried out (with a sample of 100 participants). The studies evaluated users' responses to different environmental representations of two environments, using differential semantic scales to measure key underlying factors (utility, credibility, realism, accuracy, abstraction). The first study examined simulation displays: a PC, an HTC Vive Pro 2 head-mounted display, a PowerWall Screen and a CAVE. In the second, formats were analysed: normal image, 360° image, video and 360° video. The results of this work revealed that users perceived the space differently depending on the representation displays and formats used. Such comparisons of these new means of representing architectural spaces can be helpful to researchers, architects and urban planning professionals and might provoke debate in, and be extrapolated into, the design field.

Keywords: environmental simulations; virtual reality; architectural simulation; digital techniques

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1. Introduction

Computer-based modelling and simulation are essential in building and systems' design, operation and management. Environmental simulations are essential in understanding the relationship between the built environment and psychological perceptions. Studies have shown that environmental simulations are a fundamental tool in architecture because they allow researchers, rapidly and economically, to recreate and study in isolation, in a controlled way, the influence of space on human perceptions [1,2]. Moreover, environmental simulations allow the actual, physical world to be reproduced with a high degree of realism based on the concept of "behavioural realism", i.e., the ability of an environmental simulation to create responses in users similar to those that would be evoked in the represented environment in the real world [3]; these findings are consistent with those published by other authors [4–6].

In the architectural field, many media have evolved, over time, as the relevant technologies have developed, to generate these representations. Digital techniques have been employed since the 1990s, with a notable trend being the development of the capacities for realism and interactivity [7], which has been supported by increases in processing power and enhancements to rendering algorithms, often stimulated by the entertainment industry [8]. This spectrum is being constantly, significantly enriched by innovations in computing applied to architectural simulations [9]; a key focus has been on three-dimensional models [10]—in particular, making them compatible with new developments in geographic information systems [10]. This scenario allows researchers and professionals to create, economically, environmental simulations of such realism that they are now firmly established tools usable, for example, in training contexts, even in small practices.

In this trajectory, the range of media is being expanded through the combined use of different environmental simulation formats (coding standards for its elaboration and storage) and displays (devices and platforms used for its presentation). Among the formats are photography/images and video [11] and virtual reality (VR) [12]. On the one hand, images and videos are two of the most utilised in architectural representation. These formats capture images of the real world through the action of light [13]. Similar representations can be generated by computers, i.e., renders, which are widely used when all, or part, of the architectural environment represented does not exist [14]. While these formats lack interaction, their capacity for visual realism and ease of use has made them valid and widely employed [15]. In addition, developments in spherical photographs have led to their use at commercial and scientific levels [16]. On the other hand, VR allows researchers to create architectural representations that generate in users the sensation of "being there" [17], in an interactive computer simulation that provides them with sensory information. VR provides interactivity through several devices, which can be divided into those focused on navigation, selection and manipulation and control systems [18]. The most utilised devices, in practice, are keyboards and joysticks [19].

Although VR's capacity to generate realistic environmental simulations is continually increasing [20] due to the rapid and constant advancement of both types of device, VR faces some problems. At a purely performance level, the main problem [19] is the absence of one's own body in most displays [21], which is an issue when judging certain stimuli [22]. Other limitations relate to the use of navigation devices, which can distort the experience [19], and problems with the resolution and level of detail [23]. Many VR-/health-related reports have been produced [23]. In some of these studies, the limitation of navigation devices played a role in causing differences between visual and proprioceptive information, as indicated by "sensory conflict theory" [24], but the variety of displays and use conditions makes it difficult to study symptoms [25]. More specifically, in the architectural field, they face difficulties in judging geometry [26].

Various display devices are employed to present the formats discussed above. There are PC screens, head-mounted displays and projection displays [19]. Although projections have the advantage of collaborative viewing [27], the bulk of current interest is focused on the first two [28]. Very notable, however, is the remarkably rapid, recent advancement of head-mounted displays [29], the most modern versions of which are much easier to control than were earlier versions, and which are increasingly being used in different types of applications [30], including in architecture and urban planning. These particular computer representations, although sometimes combined with auditory and/or tactile stimuli, provide only visual stimuli [19], which does not allow users to experience the richness of the real architectural environment [31] and contributes to the fact that there is still disagreement over their representation capacities [32]. However, the advances that these displays represent in the architectural field are undeniable [33].

The profound advances in representation technologies and their application have created a new research paradigm [19]. Notable is the proliferation of new displays and formats [34] and the increase in their overall use, as well as the standardisation of their utilisation by design professionals [35]. Despite this growth in VR use and research [36], as VR technologies are continually being updated, it is essential to incorporate these technological advances into the architectural and urban planning fields.

Utility is one of the main issues being discussed currently in the environmental representation context [9]. Just as a drawing with a low level of detail can contain critical information for a given purpose, an environmental representation can be helpful without being exceptionally realistic [37]. In this context, it is essential to understand that environmental simulation has two main functions [34]: to investigate human perceptions, where it has an affinity with environmental psychology [38], and to define design features [39]. These functions provide great support to design, in general, and to architecture, in particular, where environmental simulations allow architects to communicate their ideas. Consequently, environmental simulation is a tool that is indispensable for psychologists and architects [34].

In the architecture and urban planning fields, these new forms of representation have been studied in different contexts and from different perspectives. Some studies have focused on the different phases of architectural and urban design practice, including maintenance [40], resource management [41], construction [35], architectural design [42], urban planning [43] and design communication [44], where they are beneficial tools given the importance of representations in the design phase [45], and even more so in participatory processes [46,47]. Representations must be able to faithfully reflect the specific context to which they are applied [48], but digital media are very efficient due to their inherent flexibility [42]. While extensive research has taken place into the more traditional formats—such as drawings and photographs—and VR is beginning to have a solid scientific background in its application to architectural and urban representation, it features two limitations: spherical formats and many displays have not yet been evaluated, and no comparative evaluations, using the same methodologies (aimed at assessing their utility as graphic expression tools), have taken place. Nevertheless, although there is extensive technical information about the new displays and formats used in environmental representations [49], it is difficult to find comparative studies on the independent effects of new displays and formats in terms of their utility and credibility. Without broad and updated evaluations, the decisions as to which displays and formats are better fall directly to the intuition of the professional or teacher [50], with the difficulties that this may entail.

Thus, our objective is to study the adequacy of the main formats and displays currently employed in architectural and urban representations. This will make it possible not only to qualify but also to quantify the status of each of these formats and displays, useful for both researchers and professionals, involved in its use.

2. Materials and Methods

Two experiments were conducted in parallel using the same sample. The experiments had different objectives. The first experiment focused on differences in subjects' responses based on the media display utilised, and the second based on the formats used. Following research trends, the technological market and current architectural production, the formats analysed were "image", "360° image" and "virtual reality", and the displays analysed were the "PC screen" and the "HTC Vive Pro 2" VR headset. Table 1 summarises the more important characteristics of the experiments.

Different environmental representations of two environments were evaluated using differential semantic scales [51], with a focus on utility and credibility: the VR format used was an indoor scenario configured for different displays, and the HMD "HTC Vive Pro 2" was used with an outdoor scenario configured for different image and video formats.

The scenarios were organised in this way due to their technical suitability (e.g., an indoor scene could give rise to stitching problems in 360° formats due to motion parallax, and modelling an exterior scene might require many polygons, which would make processing difficult) and to allow a rigorous comparison between displays and formats based on the theory of architectural graphic expression [52]. Following this theory, the aspects "use", "presentation mode" (including navigation devices used in VR) and "graphic technique" were used for the simulations (following ceteris paribus logic). These comparisons would be helpful to researchers, teachers, architects and urban planning professionals and allow extrapolation into the design field. Figure 1 shows the stimuli used.

Table 1. Summary of the experiment.

	Experiment 1:	**Experiment 2:**
	Display Comparison	**Format Comparison**
Stimuli	Indoor space (shop)	Outdoor space (square)
Display	**1. PC (n = 20)** **3. HTC Vive Pro 2 (n = 20)** **4. PowerWall Screen (n = 20)** **5. CAVE (n = 20)**	HTC Vive Pro 2 Head-Mounted Display
Format	Virtual Environment	**1. Image (n = 20)** **2. 360° image (n = 20)** **3. Video (n = 20)** **4. 360° video (n = 20)**
Sample	80 (20 per stimulus)	**80 (20 per stimulus)**
Dependent variables	1. Credibility: abstraction, accuracy and realism 2. Spatial comprehension 3. Sense of direction 4. Help with design decisions	
Data analysis	1. Analysis of means 2. Statistically significant differences between groups 3. Statistically significant correlations between concepts and groups	

Figure 1. Stimuli (interior, **left**; exterior, **right**) used in experimentation.

2.1. Experimental Design

2.1.1. Experiment 1: Displays

The displays evaluated were a commonly used PC screen, an autonomous head-mounted display system and two large projection systems (PowerWall and CAVE).

The technical characteristics of the displays are detailed below.

- PC: Laptop with a 17.3 inch screen, 1920 × 1080 pixel resolution and navigation via a wireless joystick.
- HTC Vive Pro 2: Portable VR head-mounted display with 2448 × 2448 pixel stereoscopic screen per eye, 96° field of view, head position tracking using gyroscopes and accelerometers and navigation via a wireless joystick.
- PowerWall: Display system using a rear-projected 635 × 223 cm stereoscopic screen (using spectacles with shutters) with a resolution of 3137 × 1080 pixels, head position tracking using infrared cameras, virtual environment generation by a high-performance graphic computer and navigation via a wireless joystick.
- CAVE: Virtual reality system composed of four rear-projected 350 × 204 cm stereoscopic screens (front, two sides and floor), with a resolution of 1872 × 1080 pixels, head position tracking using infrared cameras, virtual environment generation by a set of

networked computers (connected and synchronised with each other) and navigation via a wireless joystick.

A virtual shopping area was designed as the space to be visualised (Figure 1 left). This space was chosen as no previous works have evaluated realism in this type of environment [20]. It featured sufficient complexity to evaluate spatial cognition, and its dimensions and characteristics made it ideal for the generation of a virtual environment capable of functioning with the various displays evaluated. The scenario was modelled in SketchUp, using photographic textures extracted from a real space to achieve the highest possible realism; thereafter, using the Unity3D game engine (Figure 2), specific applications were developed for the analysis of each support. The PC was the only non-stereoscopic device used.

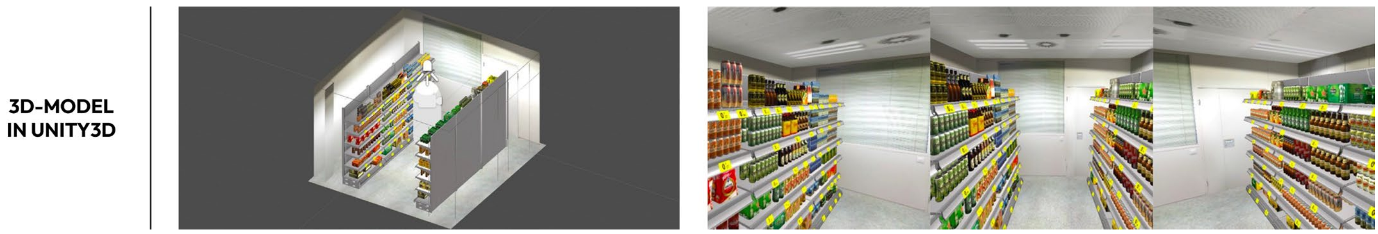

Figure 2. Three-dimensional model implemented in Unity3D.

A compilation of the displays and stimuli used during the experimental process can be seen in Figure 3.

Figure 3. Displays used in Experiment 1.

2.1.2. Experiment 2: Formats

The aim of this experiment was to compare display formats while using the same display support, an HMD. The formats evaluated were the following.

- Standard photograph/image: Photograph with a resolution of 3840 × 2160 pixels, taken with a GoPro Hero 7 Silver camera (GoPro, City: San Mateo, California (USA).), at a height of 165 cm to simulate eye level. Given the inherent limitation of this format in capturing an entire environment, the most representative point of view was selected [53].
- Spherical panoramic l resolution of 4096 × 2048 pixels, from photographs taken by seven GoPro Hero 7 Silver cameras attached to panoramic recording mounts (in the same positions and heights as used in standard images).
- Video: Video (with sound) with a resolution of 3840 × 2160 pixels at 25 frames per second, taken with a GoPro Hero 7 Silver camera. The same point of view and height were used as in standard images.
- Spherical panoramic video: 360° × 180° equirectangular video (with sound) with a total resolution of 4096 × 2048 pixels at 25 frames per second, from images taken by seven GoPro Hero 7 Silver cameras attached to panoramic recording mounts (in the same positions and heights as used in standard images).

An outside area of the Universitat Politècnica de València campus was chosen as the setting, which included views of a square, green areas and classrooms. It is known as the "Agora" and is located in a central area of the Vera campus of this university (Figure 1 right). This outdoor space was chosen because it allowed us to capture the ambient sound and movement of people necessary for the videos to be evaluated. The HTC Vive Pro 2 HMD (HTC Corporation, Xindian, New Taipei, Taiwan) was used as a display support due to its portability and ability to support the four formats to be evaluated. A compilation of the formats and stimuli used during the experimental process can be seen in Figure 4.

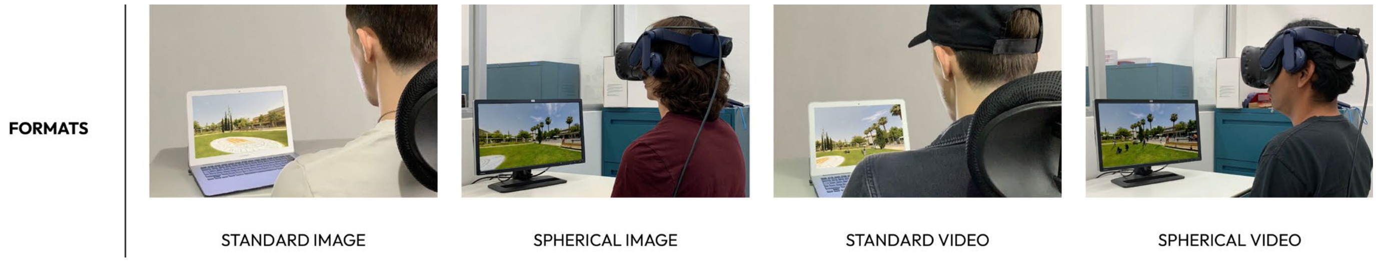

Figure 4. Formats used in Experiment 2.

2.2. Measurements

The same space assessment questionnaire, with seven-point Likert-type scales, was used for both experiments. The questionnaire included three sets of self-assessment questions.

The utility of simulations was measured using the concept of "credibility" and its three dimensions: "accuracy", "realism" and "abstraction" [33,50,54,55]. This complex notion amalgamates multiple aspects underlying the perceived quality of representations [56]. Since Appleyard defined the aspects involved in this concept [57], others authors have redefined and condensed them into: "accuracy", the precision that allows the observer to acquire knowledge similar to that provided by an unlimited observation of the design [54,58]; "realism", the generation of virtual experiences close to real-world experiences [59] and "abstraction", which relates to the level of detail contained in representations [55]. Credibility has been widely studied in the context of traditional representations. Although measures based on traditional sciences may not be sufficiently robust or sensitive to fully evaluate new media, the underlying arguments for the use of these methodologies remain valid, and they have demonstrated the significant value that VR brings to many disciplines. In this sense, "credibility" has been proposed as part of a valid approach to the evaluation of virtual technologies and renders [60], in particular, in the making of comparisons between VR and traditional architectural representations [55]. Therefore, it could be argued that complementing "credibility" with the specific aspects under study (depending on the case), such as comprehension and orientation (taking into account their importance in the built environment context) [61] and virtual representations of the built environment [62], constitutes a valid transversal approach to studying and comparing the different design supports currently available for architectural graphic design.

The comprehension of space was measured through the expressions "It is easy for me to understand the space" and "I could easily orient myself", both related to making design decisions [50,63]. Decision making was assessed through the expression "it would help me make design decisions".

In the assessment of the representations, the variables were arranged in the same sequence in all cases.

2.3. Participants

One hundred subjects participated in the study. The number of participants was determined using statistical methods [64]. The relevant calculations indicated that 20 respondents per stimulus would be sufficient to achieve the desired levels of alpha and beta errors; thus, in the first experiment, with five stimuli, 100 subjects participated, and in the second, with four stimuli, 80 participated. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of the Universitat Politècnica de València (P1_25_07_18; 25 July 2018).

The requirements for participation were that the subjects had never previously viewed the scenarios or suffered from claustrophobia, epilepsy or nausea (the use of 3D immersive technologies can be harmful in these cases [65]). The characteristics of the experimental subjects are shown in Table 2.

Table 2. Sample characteristics.

	Gender				Age				
	Male		Female		20 to 35		36 to 50		Total
Experiment 1	55	55%	45	45%	53	53%	47	47%	100
Experiment 2	47	59%	33	41%	42	53%	38	48%	80

2.4. Procedure

The experimental procedure was briefly explained to the subjects, who signed the relevant informed consent documents. Subsequently, they were given instructions on how to employ the technology and, for the evaluation of the 3D virtual environments, they practised with a scenario designed to allow them to become familiar with the navigation. To create a sense of tranquillity, before the experiments, the subjects sat down and listened, through headphones and with their eyes closed, to a relaxing two-minute audio clip. The subjects were then shown the randomised stimuli, always starting at the same point and angle of vision. They observed the environments in detail for three minutes; in the virtual environments, they could move freely.

Finally, while the subjects viewed the stimuli, the researcher orally asked the questions posed in the questionnaire. Some 80 of the participants from experiment 1 subsequently participated in experiment 2 (after taking a ten-minute break). The data obtained were treated statistically using the SPSS software (https://www.ibm.com/products/spss-statistics, accessed on 7 November 2023). The data treatment and techniques are shown in Table 3.

Table 3. Data treatment phases and techniques.

1.	**Descriptive analysis of the ratings**	Based on users' responses	Analysis of means Standard deviation
2.	**Analysis of significant differences in ratings**	(a) Based on the profile of the subject (gender and age)	Mann–Whitney U
		(b) Based on the stimuli analysed (displays and formats)	Kruskal–Wallis
3.	**Analysis of relationships between variables**	(a) Analysis of relationships between the variables that measure the users' responses	Spearman correlation
		(b) Analysis of relationships between the variables that measure the users' responses and the stimuli (displays and formats)	

a. Descriptive analysis of the ratings
   First, a descriptive analysis was carried out to detect trends in the results. The values for each variable were normalised to their z scores to simplify comparisons.
b. Analysis of significant differences based on the subjects' profiles.
   Although it was not the study's main object, we tested for the existence of statistically significant differences in the responses based on the gender and age of the participants. The statistical analyses applied were based on the normality of the data for each

variable, which were assessed using the Kolmogorov–Smirnov (K–S) test. Due to the non-normality of the data (K–S, $p < 0.05$), the comparison between both groups (gender: male vs female/age: 20–35 vs. 35–50) was made through a non-parametric Mann–Whitney U test (also referred to as the Wilcoxon rank sum test). The Mann–Whitney U test is a non-parametric method to detect whether two samples come from the same distribution, or to test whether the medians between comparison groups are different. It is based on the ordering of the data and the use of ranks to perform the contrast, with two statistics (the U Mann–Whitney and the W Wilcoxon) and a significance level. We will look at the significance level ($p < 0.05$) to identify the existence of significant differences.

c. Analysis of significant differences between the evaluated stimuli
An analysis was undertaken to identify any statistically significant differences in the respondents' responses based on the display (experiment 1) or format (experiment 2) visualised. The statistical analyses applied were based on the normality of the data, using the Kolmogorov–Smirnov (K–S) test. Due to the non-normality of the data (K–S, $p < 0.05$), the comparison between groups (displays: PC-HTC Vive Pro 2-PowerWall Screen–CAVE; formats: image–360° image–video–360° video) were made through a non-parametric Kruskal–Wallis test. The Kruskal–Wallis test compares whether different samples are equally distributed and therefore belong to the same distribution. It is an extension of the Mann–Whitney test for more than two groups. Where differences were found between groups, the samples were compared in pairs. Again, we will look at the significance level ($p < 0.05$) to identify the existence of significant differences.

d. Relationship between variables and stimuli
An analysis was undertaken to identify any statistically significant correlations, using Spearman's Rho correlation coefficient for non-parametric samples, firstly between the variables evaluated, and subsequently between the variables and the stimuli displayed.

3. Results

3.1. Experiment 1: Displays

3.1.1. Descriptive Analysis of the Ratings

In the first place, Figure 5a shows the means, standard deviations and standard errors for each variable and display analysed (as well as statistically significant results of the correlation and difference tests for interpretation). First, lower ratings (consistently below average) were observed, in all aspects, for the PC-based visualisation than for the other technologies.

In the second place, the HTC Vive Pro 2 HMD achieved the best ratings for "realism" and "help with design decisions". Third, the two non-surround systems, PC and Powerwall, achieved the worst ratings for "orientation".

3.1.2. Analysis of Significant Differences

a. Based on the profile of the subject (gender and age)

The Mann–Whitney U test did not identify any significant differences in the evaluations of the six variables, either by age or gender (Table 4).

b. Based on the stimuli analysed (displays)

On the other hand, the Kruskal–Wallis test found significant differences in four of the six variables evaluated (Figure 5c). For "abstraction" and "I could easily find my way around", the significant differences were between the Powerwall and CAVE. Both in "realism" and "help with design decisions", the significant differences were between the PC (lower rating) and the VR HTC Vive Pro 2 HMD and the CAVE (higher rating).

Table 4. Differences by age and gender with Mann–Whitney U and Wilcoxon W test statistics.

	Abstraction	Accuracy	Realism	Comprehension	Orientation	Helps with Design Decisions
Differences by Age (20 to 35/35 to 50)						
Mann–Whitney U	1103.00	913.50	1030.50	1164.50	963.50	1147.00
Wilcoxon W	2231.00	2344.50	2461.50	2595.50	2394.50	2578.00
Z	−1.00	−2.34	−1.52	−0.62	−2.09	−0.69
Asymp. Sig. (2-tailed)	0.316	0.059	0.128	0.537	0.067	0.488
Differences by gender (male/female)						
	Abstraction	**Accuracy**	**Realism**	**Comprehension**	**Orientation**	**Helps with Design Decisions**
Mann–Whitney U	1091.00	1185.00	1107.00	1203.50	1073.00	1198.00
Wilcoxon W	2126.00	2725.00	2647.00	2743.50	2613.00	2233.00
Z	−1.03	−0.37	−0.93	−0.26	−1.22	−0.28
Asymp. Sig. (2-tailed)	0.301	0.710	0.354	0.795	0.222	0.780

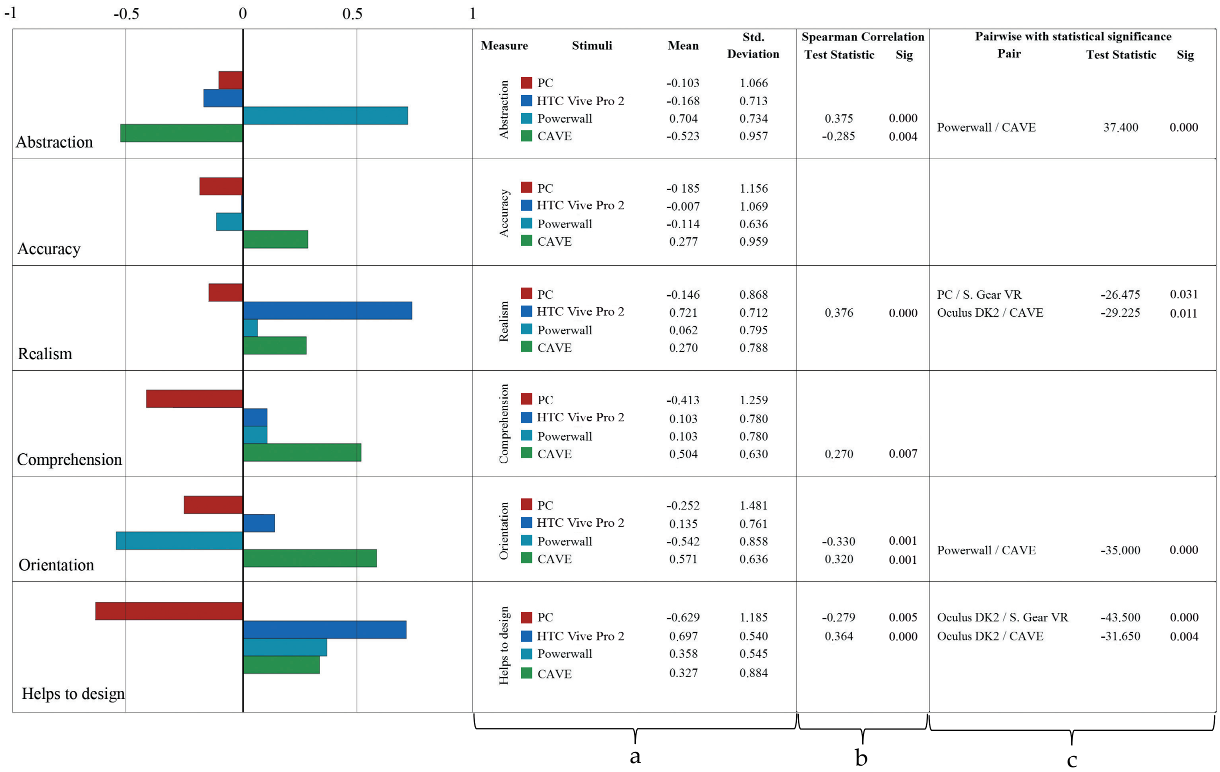

Figure 5. Means, standard deviations, Spearman correlation and pairwise comparison for each of the variables and displays analysed.

3.1.3. Analysis of Relationships between Variables

a. Between the variables that measure the users' responses

Table 5 shows the correlations between the variables analysed. As to the relationships between the six dependent variables, on the one hand, the users interpreted "abstraction" and "accuracy" as antagonistic concepts and unrelated to the rest of the variables. On the other hand, "realism", "comprehension of space", "ease of orientation" and "helps with design decisions" were completely interrelated.

b. Between the variables that measure the users' responses and displays

Regarding the relationships between stimuli and ratings (Figure 5b), there was statistical significance in all concepts.

Table 5. Correlations between the variables analysed. The asterisks indicate the significance level (* $p < 0.05$, ** $p < 0.01$).

		Abstraction	Accuracy	Realism	Easy to Comprehend the Space	Easy to Orient Myself	Helps with Design Decisions
Abstraction	coef. Sig.		−0.395 ** 0.000	−0.087 0.387	−0.019 0.850	−0.089 0.378	0.193 0.054
Accuracy	coef. Sig.	−0.395 ** 0.000		0.191 0.056	0.203 * 0.043	0.209 * 0.037	−0.053 0.600
Realism	coef. Sig.	−0.087 0.387	0.191 0.056		0.351 ** 0.000	0.287 ** 0.004	0.586 ** 0.000
Easy to Understand the Space	coef. Sig.	−0.019 0.850	0.203 * 0.043	0.351 ** 0.000		0.452 ** 0.000	0.382 ** 0.000
Easy to Orient Myself	coef. Sig.	−0.089 0.378	0.209 * 0.037	0.287 ** 0.004	0.452 ** 0.000		0.352 ** 0.000
Helps with Design Decisions	coef. Sig.	0.193 0.054	−0.053 0.600	0.586 ** 0.000	0.382 ** 0.000	0.352 ** 0.000	

3.2. Experiment 2: Formats

3.2.1. Descriptive Analysis of the Ratings

Figure 6a shows the means, standard deviations and standard errors for each variable and display format analysed (as well as the statistically significant results for the correlation and difference tests for interpretation). The results revealed two trends. On the one hand, there were differences between images and video for the concepts "abstraction" and "accuracy". On the other hand, there were differences between the traditional formats (worst rated) and 360° (best rated) for the other concepts.

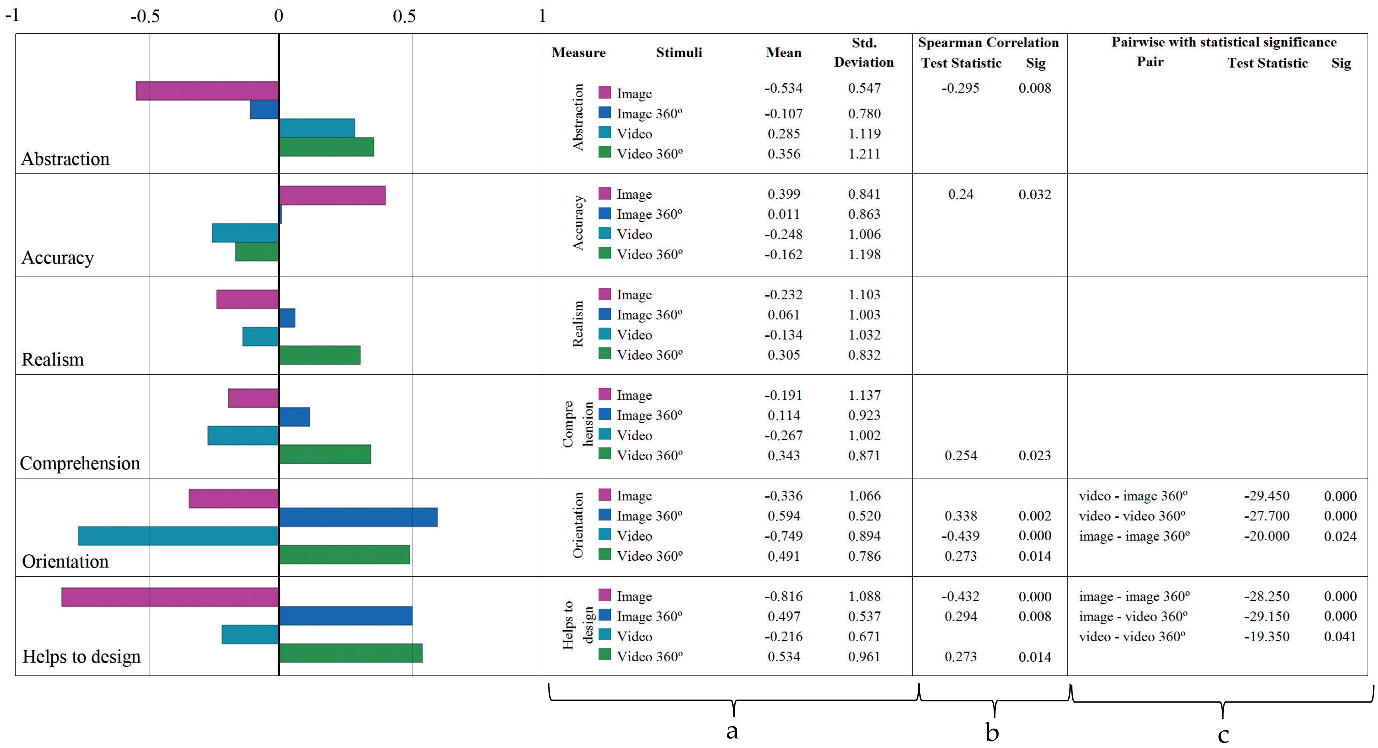

Figure 6. Means, standard deviations, Spearman correlation and pairwise comparison for each of the variables and formats analysed.

3.2.2. Analysis of Significant Differences

a. Based on the profile of the subject (gender and age)

The Mann–Whitney U test did not identify any significant differences in the evaluations of the six variables, either by age or gender (Table 6).

Table 6. Differences by age and gender with Mann–Whitney U and Wilcoxon W test statistics.

Differences by Age (20 to 35/35 to 50)						
	Abstraction	**Accuracy**	**Realism**	**Comprehension**	**Orientation**	**Helps with Design Decisions**
Mann–Whitney U	690.50	787.50	754.50	733.00	794.00	719.00
Wilcoxon W	1431.50	1528.50	1657.50	1636.00	1535.00	1622.00
Z	−1.06	−0.11	−0.44	−0.71	−0.04	−0.78
Asymp. Sig. (2-tailed)	0.287	0.916	0.660	0.478	0.968	0.434
Differences by gender (male/female)						
	Abstraction	**Accuracy**	**Realism**	**Comprehension**	**Orientation**	**Helps with Design Decisions**
Mann–Whitney U	642.00	646.00	719.00	742.50	609.50	737.00
Wilcoxon W	1203.00	1774.00	1280.00	1870.50	1737.50	1865.00
Z	−1.34	−1.32	−0.58	−0.37	−1.71	−0.39
Asymp. Sig. (2-tailed)	0.180	0.188	0.562	0.715	0.087	0.699

b. Based on the stimuli analysed (formats)

Statistically significant differences were found (Figure 6c) based on the stimuli used between the traditional and 360° formats for the concepts "easier to orientate myself" and "it would help me with design decisions".

3.2.3. Analysis of Relationships between Variables

a. Between the variables that measure the users' responses

The correlation table (Table 7) shows that, in terms of the relationships between the six dependent variables, the results of the first experiment are repeated. On the one hand, "abstraction" and "accuracy" appear as antagonist concepts unrelated to the other variables, and, on the other, "realism", "comprehension of space", "ease of orientation" and "helps with design decisions" are entirely interrelated.

b. Between the variables that measure the users' responses and formats

As to the relationship between formats and variables (Figure 6b), a positive correlation was shown to exist between the 360° panoramic formats and the three spatial comprehension-related variables.

Table 7. Correlations between the variables analysed. The asterisks indicate the significance level (* $p < 0.05$, ** $p < 0.01$).

		Abstraction	**Accuracy**	**Realism**	**Easy to Comprehend the Space**	**Easy to Orient Myself**	**Helps with Design Decisions**
Abstraction	coef.		−0.480 **	−0.064	0.084	−0.046	−0.004
	Sig.		0.000	0.573	0.461	0.683	0.975
Accuracy	coef.	−0.480 **		0.276 *	0.231 *	0.162	0.143
	Sig.	0.000		0.013	0.039	0.150	0.206
Realism	coef.	−0.064	0.276 *		0.518 **	0.411 **	0.349 **
	Sig.	0.573	0.013		0.000	0.000	0.002

Table 7. *Cont.*

		Abstraction	Accuracy	Realism	Easy to Comprehend the Space	Easy to Orient Myself	Helps with Design Decisions
Easy to Understand the Space	coef. Sig.	0.084 0.461	0.231 * 0.039	0.518 ** 0.000		0.359 ** 0.001	0.248 * 0.026
Easy to Orient Myself	coef. Sig.	−0.046 0.683	0.162 0.150	0.411 ** 0.000	0.359 ** 0.001		0.548 ** 0.000
Helps with Design Decisions	coef. Sig.	−0.004 0.975	0.143 0.206	0.349 ** 0.002	0.248 * 0.026	0.548 ** 0.000	
Video (vs. Image)	coef. Sig.	0.277 * 0.013	−0.193 0.086	0.076 0.502	0.033 0.771	−0.128 0.258	0.119 0.293
360° (vs. Non-360°)	coef. Sig.	0.125 0.271	−0.069 0.542	0.176 0.119	0.234 * 0.037	0.545 ** 0.000	0.530 ** 0.000

4. Discussion and Conclusions

The present study investigated the adequacy of the main displays and formats currently used in architectural and urban representations. Adequacy was assessed using differential semantic scales, with a focus on utility and credibility. Two experiments were carried out: a comparison of displays (image, 360° image, video and 360° video) and a comparison of formats (PC, HTC Vive Pro 2, PowerWall Screen and CAVE).

The main contribution of this work is its comparison of displays and formats using the same methodology; this allowed us to analyse their utility as graphic expression tools. While much research has been undertaken into the most traditional formats, such as the many forms of drawings and photographs [66–68], and the VR format is beginning to have a solid scientific background in terms of architectural and urban representations [9,43,69], to the best of the authors' knowledge, no previous works have compared users' responses to different environmental representations.

At the results level, the following aspects should be highlighted.

First, in the comparisons of the analysed displays, lower ratings (consistently below average) were observed in all aspects of the PC-based visualisations than for the other technologies. This result is similar to that obtained by Pallavicini et al. [70] in the gaming arena, who compared immersive (VR) and non-immersive (desktop PC) conditions. They found that a more immersive experience provides the user with an impressive and enjoyable gaming experience, with characteristics profoundly different from more traditional non-immersive displays. In our case, the VR headset HTC Vive Pro 2 achieved the best ratings for "realism" and "helps with design decisions". Nevertheless, other studies, such as de Vasconcelos et al. [71], found that students perceived the 360° panorama conditions as being more realistic than the VR conditions, but design professionals perceived no difference. In our case, the good results achieved for the VR experience might lead to the assumption that the graphic resolution (PPI) of the VR headset is a key factor in achieving a realistic experience due to the closeness of the screen to the observer. Furthermore, it should be noted that the two displays with the worst ratings in "orientation", the PC and Powerwall, were the only two non-enveloping systems. The best rated was the CAVE, which is an enveloping system that allows the user to see his/her own body during the simulation. Nonetheless, it is noteworthy that the enhancements made to VR HMDs, i.e., to their controllers, display resolution, mobility, ease of use, costs and maintenance, make companies and research centres choose them over CAVE systems [72].

Second, the comparisons of the formats revealed differences between images and video for "abstraction" and "accuracy". The image format achieved better results than the other formats only for "accuracy". Video obtained better results for "abstraction". Taking the remainder of the concepts, it is noteworthy that traditional formats were the most poorly rated. Nevertheless, the 360° formats were the most highly rated. Shinde et al. [73]

also proposed that 360° panoramas provide a higher sense of presence than conventional simulation methods and that a combination of 360° panorama technologies and HMDs have significantly increased immersion over other options.

Third, concerning the semantic rating scales, "abstraction" and "accuracy" appear as antagonistic concepts unrelated to the other variables. On the other hand, "realism", "comprehension of space", "ease of orientation" and "helps with design decisions" are entirely interrelated.

Finally, in both experiments, an examination was made of whether significant differences by gender and age existed, but none were found. In this sense, other studies also evaluated 360° video, such as Coelho et al. [74], and did not find that gender impacted system usability, presence, satisfaction or effectiveness.

This study has limitations that open avenues for future research. The results may have been conditioned by the specific environments studied; thus, they may be different with altered spatial properties or different spaces. In this regard, it should be mentioned that the exterior space was not used to study the formats due to the relative difficulty of replicating large spaces three-dimensionally at a photorealistic level. Future studies could employ the new three-dimensional data collection techniques to address this specific investigation. It should also be noted that the viewing mechanisms for the 2D and 360° video/images differed, which might have created different experiences [75]. In addition, future works could benefit from using neuroscientific methods, such as electroencephalography (EEG), to extend the application of objective responses, as a compliment to subjective responses, to the understanding of the underlying basis of users' experiences in environmental simulations.

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