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Spatial Skills and Perceptions of Space: Representing 2D Drawings as 3D Drawings inside Immersive Virtual Reality

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Abstract: Rapid freehand drawings are of great importance in the early years of university studies of architecture, because both the physical characteristics of spaces and their sensory characteristics can be communicated through them. In order to draw architectural spaces, it is necessary to have the ability to visualize and manipulate them mentally, which leads us to the concept of spatial skills; but it also requires a development of spatial perception to express them in the drawings. The purpose of this research is to analyze the improvement of spatial skills through the full-scale sketching of architectural spaces in virtual immersive environments and to analyze spatial perception in reference to the capture of spatial sensations in virtual immersive environments. Spatial skills training was created based on the freehand drawing of architectural spaces using Head Mounted Displays (HMD) and registered the spatial sensations experienced also using HMD, but only in previously modeled realistic spaces. It was found that the training significantly improved orientation, rotation and visualization, and that the sensory journey and experimentation of architectural spaces realistically modeled in immersive virtual reality environments allows for the same sensations that the designer initially sought to convey.

Keywords: spatial skills; spatial perception; immersive virtual reality; 3D drawing; sketching; architecture

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1. Introduction

Architectural professionals must efficiently communicate their ideas; therefore, they must master graphic representation as it is the natural method of communication for the dissemination of their architectural designs. Among the various techniques of graphic representation, freehand drawing or sketching are the most used by architects and designers to quickly capture and communicate the instant wave of ideas as they appear in their mind [1]. In a design process, ideas develop incrementally from an abstract level to a concrete level by moving from a schematic level to a detailed level [2], hence the need for rapid freehand sketches. The architecture student must learn in the first few months of university this important communication tool, which is essential for the traditional process of teaching architectural design and fundamental in the initial and conceptual phases of design. Sketches continue to be the most significant tools [3], even above models or physical scale models, which are difficult to modify during the stages of communication or while debating the design. These scaled models pose a couple of serious complications: they do not lend themselves to the observation of interior spaces [4], and their assemblage is unnecessarily time-consuming.

In addition to the communicative function, rapid freehand drawings allow us, through the lens of perception, to imagine how the designed architectural space might ultimately function [5]. It can even allow us to directly experience an architectural space despite not being physically inside or in front it. Spaces based on the observation of sketches can be keenly perceived due to their ability to stimulate the observer into experiencing new spatial realities. They allow the observer to perceive the represented space as if it were real, permitting them to be able to walk around, observe the environment, enter and exit at will, feel temperatures and textures, smell, etc. [6]. Although architecture is perceived predominantly with our sense of sight, it is through all our senses that the experience comes to complete fruition. It is represented through drawings that put a special emphasis on form with parameters like measurements, proportion and scale, materials, color, and so on. In the field of ephemeral architecture, it has taken a huge dimension in the world of design in recent years. Currently, the representation of architecture has reached its simplest and most effective expression calling on the senses and emotions through forms and materiality, always seeking maximum expressiveness with a minimum of space. In architectural education, the student must be able to perceive and interpret sketches, not only in their exact forms, but also in sensory-based forms which respond to a vital imperative in architectural studies: a special sensitivity to both the natural and constructed environment.

In contrast to technical drawing, there is the act of drawing that is linked to natural abilities and special skills, which complement the creative and design processes. The act of drawing is not only about exteriorizing the pre-existing mental models [7], but it also deals with the development of ideas while drawing and searching for new spatial relationships. Fundamentally, this happens in the initial phases of the product's creation process [3].

The technique of manual drawing is the essential catalyst for an action which involves not only sight but also other senses that are found in the individual's corporeal and unconscious memory. This additionally allows for the reflection of past experiences [6] as well as various mental, cognitive and imaginative processes, which are aimed at the draftsperson so they are able to develop the skills required to manipulate the three dimensions.

Consequently, in order to draw architectural spaces, it is necessary to have the ability to mentally visualize and manipulate them in any position and to know the techniques of representation systems, which directly leads to the concept of spatial skills. Furthermore, it is also necessary to develop one's own spatial perception to capture the sensations expressed in the drawings and express them in the designs.

1.1. The Spatial Skills and the Spatial Perception

Spatial skills have been the subject of extensive research for more than a century and are an important line of research in cognitive and educational psychology. Researchers in the field of human intelligence agree that our intelligence is not unique and that it consists of several different components. All the theories and studies carried out in this field concur that one of the components of intelligence is directly related to our visual and spatial capacities as they function within the mental representation of two- and three-dimensional spaces, as well as facilitate the resolution of spatial problems, whether real or imaginary.

Spatial skill is a component of human intelligence. It is understood as the ability to generate, retain, retrieve, and transform well-structured visual images [8]. However, as seen in the definition itself, there is no clear agreement about the subskills or components that shape this ability [9]. For example, McGee [10] distinguishes five components of spatial skills: spatial perception, spatial visualization, mental rotation, mental relationships, and spatial orientation.

Recent research such as the Cattell–Horn–Carroll Model of Intelligence [11] shows eleven spatial skills that constitute Spatial Cognition, while even more recent studies, based on the previous model and new contemporary theories, conceptualize the Spatial Cognition or Visual Processing consisting of 25 factors [12]. Many of these factors are interrelated yet psychometrically measurable, thus rendering them highly important as they relate to university educational success.

Some researchers, like Carroll [13], recognize only two components: spatial visualization, understood as the ability to mentally handle complex forms, and mental rotation, defined as the mental speed to rotate simple forms and recognize them whilst in another position. The simplification of the components of spatial skills responds in general to the relationship that researchers seek with the possibility of training these skills in the field of engineering, and looks to generate a positive impact [14].

For the methodological and practical effects of this research we will consider the two components proposed by both Tartre [15] and supported by Sorby [16]: spatial visualization and spatial orientation. The spatial visualization component entails mentally moving an object, whereas the spatial orientation component requires the ability to mentally move a given viewpoint while the object remains fixed in space. The spatial visualization component is subdivided in two categories, Mental Rotation and Mental Transformation, the difference being that with Mental Rotation, the whole object is transformed by rotating it in a given space, while with Mental Transformation, only a specific part of the object undergoes some kind of transformation (Figure 1). We consider that this scheme is better adapted for the research concerning the exploration of architectural spaces. This is due to the fact that the objects that must be mentally manipulated and understood are objects or spaces in which the user can enter and even (mentally) travel through, thus obtaining perceptions or sensations within them as opposed to other objects in which the observer does not have that possibility.

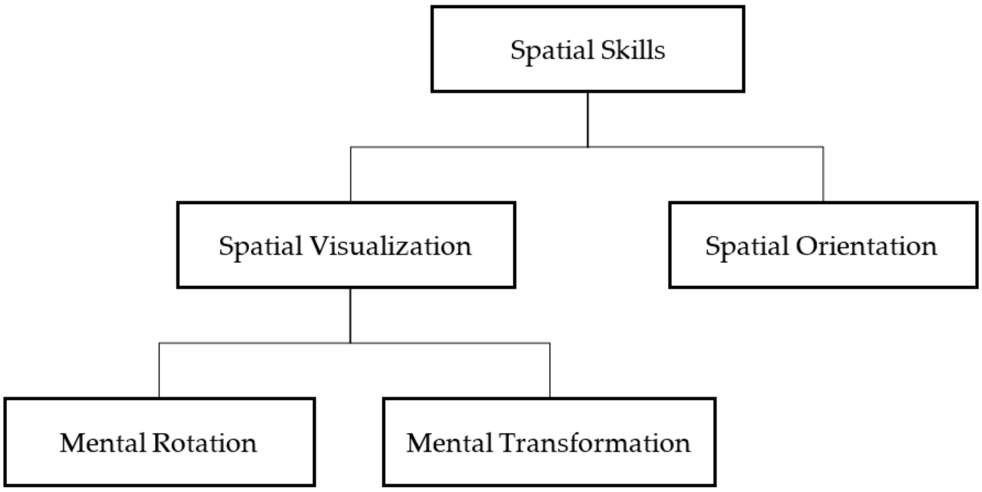


Figure 1. Classification of spatial skill [15].

On the other hand, the perception of extrapersonal space, or simply spatial perception, involves not one but many specific skills. For example, within the visual domain, they include locating points in space, determining the orientation of lines and objects, evaluating the location in depth, observing the geometric relationships between objects and processing movement among many others [17]. Although there are proposals that consider spatial perception as a component of spatial skills [8,18], mainly due to simplified or different definitions of perception, in this research we will consider perception as an independent aspect of spatial skills because we want to notice how students know and understand the architectural space through the senses and emotions where, among others, the shapes, colors, and design materials influence.

1.2. The Importance of Spatial Skills and Perception in the Field of Architecture

For the design of three-dimensional spaces in real and virtual and interactive environment, a balanced combination of spatial skills and spatial perception must be achieved. Regarding spatial skills, it is suitable to have a good level in each of the components because benefit the designer to draw in 3D. These components provide the designer the ability to manipulate "mentally" the positions of the object and their parts, the relationships between them and their volumetric properties which help the designer to draw in 3D, giving coherence and cohesion to the projected space. As for spatial perception in the field of architecture, the experience of space by means of the senses is given special consideration so that the qualities which are not considered in the drawing, such as color, texture, lighting and sounds, become fundamental, thus allowing for the development of a spatial sensitivity. This type of sensitivity is understood as the unconscious awareness of the body in the world as a result of intersubjective interactions, and the receptiveness to the transitory amalgamation of sensory signals that make up the sense of place at a given time [19].

About the balance between spatial skills and spatial perception (including spatial sensibility and emotions) in the architectural field, it is given a human and poetic dimension that can guide students towards the creation of spaces as embodied experiences, rather than abstract constructions, therefore, the teaching of architecture issues should focus on developing both skills equally, on the one hand the spatial skills and on the other the spatial perception and sensitivity, especially at the beginning of the student's education, skills that should be consistent with the competences covered in the current architectural pedagogy [20].

There are some studies that also link spatial skills with spatial creativity, a necessary component to undergo architectural design, such as the research of Suh and Cho [21]. Their research found a correlation between spatial visualization and mental rotation as three-dimensional volumetric design is creatively generated, and in terms of spatial strategies, individuals with high spatial skills show strengths in the formation of shapes, while those with medium and low spatial skills show strengths in additional approaches of a simpler nature. However, this research, like many others, has failed to establish a real and direct link of spatial skills with spatial creativity and this is because the complexity of architectural designs requires the interaction of multiple cognitive skills and not just one or two of them [21]. The truth is that learning spatial skills is an important supporting strategy in the pedagogy and teaching of architecture at the beginning of the student's university studies, such that it can then provide a basis on which to build more complex skills for solving complex real-world problems. Nevertheless, they are not necessarily predictive of academic success towards the end of a degree plan [20] due to the different cognitive skills required, but they are definitely at the beginning stages of their studies when the student is first learning to express their ideas through drawing.

Several authors mention that there is a direct relationship between academic performance, motivation, and self-regulated learning. They state that the ability to effectively visualize graphics in university drawing courses can affect academic performance [21–23]. A study conducted by Burton and Dowling [24] with high school students determined that the ability to visualize, understood as the ability to understand spatial shapes and mentally rotate them in two dimensions in relation to a model, was a predictor for determining a student's academic success. This was further supported by Potter, Potter, van Der Merwe, Kaufman and Delacour [25], who concluded that the student's ability to understand spatial relationships in three dimensions influenced academic success. Both studies show that there is a direct relationship between academic performance in engineering studies and spatial abilities. In the specific case of a university degree in architecture, because it is within the set of science, technology, engineering, arts and math (STEAM) disciplines and because it has several subjects related to drawing and descriptive geometry, there is also the same relationship in which spatial skills are fundamental to success in the initial courses of design and drawing [26], although most research has focused largely on the field of engineering and its relationship with spatial skills [27–29].

1.3. Training of the Spacial Abilities

Further research has demonstrated effective training methods to improve spatial skills in real open environments [30,31]. However, given the rise of emerging technologies such as virtual reality, an increasing body of research is seeking to develop spatial skills in virtual worlds [32,33], in immersive and interactive environments [34], and in virtual navigation experiences [35–37].

Different courses, training exercises and different technologies have been developed in the last decades to address the low levels of spatial skills available to students with technical degrees. Numerous and specific remedial trainings are widely available. We will mention those based on virtual technologies to improve spatial skills and knowledge of architecture issue [38] and trainings focused on the improvement of visualization and rotation components through human–computer interaction with screens [39–41].

In the specific field of architecture and spatial skills research, it is known that there are three areas that require further study. The first is the relationship between spatial skills and design performance. The second is the development of domain-specific tools that measure spatial skills. The third is the use of virtual reality technology in spatial skills training [42]. In the search of this last deficiency, we do not have any evidence of training methods (designed) through the drawing of architectural spaces which propose the interactivity and immersion of the student, and that allow us to know if the experience that the student acquires in virtual environments, induces them to have a similar behavior in the real world and in similar circumstances. In our research we have proposed to create a training system based on immersive virtual reality in which the student can interact to perform sketches of architectural elements that promote the development of mental actions of rotation, visualization, perception and orientation in order to improve their spatial skills and, therefore, receive the necessary training to perform the action of drawing.

1.4. The Immersive Virtual Reality

Virtual reality (VR) is a synthetic environment created by computer technologies that allow the user to see realistic scenes or objects. In its most primitive mode, the user can see these scenes or objects on a screen and can interact with them through different control devices (mouse, keyboard, joysticks, knobs, controllers, etc.). Currently, the user can visualize the virtual environments through devices known as glasses or "virtual reality helmets" (Figure 2) with immersion characteristics that can even be accompanied by other devices, such as gloves or special suits. The combination of these devices allows for a much greater interactive experiences with the environment as well as an increased sensorial perception that intensifies the sensation of reality. The user, while immersed in the VR system, cannot see the real world around them due to their entire perceived environment is synthetic and simulated; nevertheless, meaningful interaction can still be achieved.

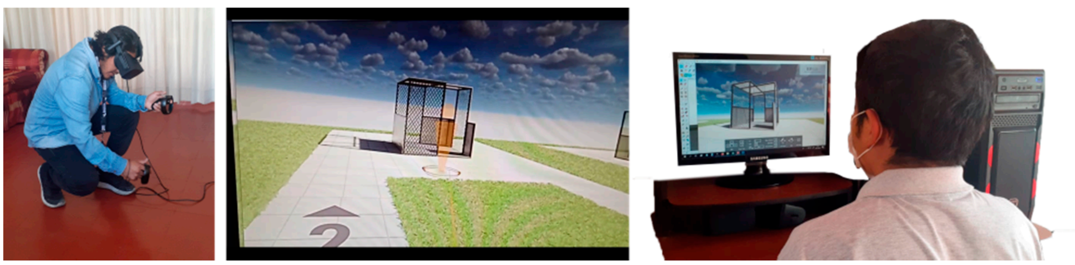


Figure 2. Example of VR uses.

In the fields of engineering and architecture, virtual reality technology is applied and supported by the use of 3D modeling tools and visualization techniques as part of the design process. VR allows architects and engineers to see their project in 3D and to gain a better understanding of how it works. In addition, they are able to detect any potential defects or risks prior to implementation. This also allows the design team to observe their project within a safe environment, make operational simulations and make all the necessary changes.

Virtual reality has been integrated into the work routines of architects and engineers and is therefore used from the beginning stages of the design life cycle. For example, VR is implemented from the initial concept stage to the construction and execution stages, positioning itself as an important tool to be incorporated into the work routines in order to review each stage of the project and check for flaws, structural weaknesses or other design issues.

1.5. Drawing and Immersive Virtual Reality

Since its emergence, virtual reality has shown significant potential in architectural design especially during early design activities. In the last decade, the facility and accessibility of equipment and software has caused innumerable investigations but not with enough attention to the results and possibilities of architectural design and drawing in immersive virtual environments [43].

Some investigations have probed that immersive virtual reality allows designers to create new points of view by means of an immersive experience and the possibility to walk around the three-dimensional sketches [44]. Other studies have highlighted the positive effect of VR-based design that makes a significant leap forward allowing for a development of design solutions in the same creative process [45]. Other researchers have successfully integrated key attributes of hand drawing into a new virtual reality medium for design development. Yang and Lee [46] have shown that three-dimensional drawings in immersive virtual reality help designers reduce their dependence on external representations while improving their mental processes for the transformation and consolidation of their ideas. Furthermore, the application of immersive virtual reality extends to solution spaces and has an overall positive effect on the problem-solving process as a whole.

In the field of perception of spaces, virtual environments have demonstrated to maintain the feeling of presence within the digital 3D models which causes the important advantage of conveying overall design intentions similar to physical models, constructed to improve the perception of designs developed by drawings, giving the users an immediate feedback not possible within CAD or traditional design media, helping them to explore and express ideas unlike traditional methods [43].

The sense of presence created by virtual reality is an integral component of a system that relies on automatic physiological responses. Some researchers suggest that virtual environments generate strong emotional and physical responses and have which are comparable to real-life tests, demonstrating the validity of this medium for psychological assessment studies [47]. Studies related to the field of architectural design indicate the appropriateness of using VR to simulate the sensation of presence in a corresponding real physical space [48,49]. These studies support the idea that virtual environments, in combination with virtual reality, could be considered as an alternative method when investigating the impact of spatial stimuli.

2. Objectives and Hypothesis

The perception of architectural spaces and the spatial skills used to represent them and manage their three-dimensionality are essential conditions that architecture students must have to successfully undertake their university studies. The frequent low levels of spatial perception and the poor development of spatial skills are not the only reason for high dropout rates amongst architecture majors, but they can also contribute to low professional performance in those who manage to complete their studies. This is because a fundamental task of the architect is the creation of spaces for the development of human activities.

The aim of this research is twofold: to analyze the improvement of spatial skills in first-year architecture students (freshmen) by training them in life-size sketching of architectural spaces in virtual immersive environments, and to analyze the visuospatial perception in reference to the acquisition of spatial sensations in virtual immersive environments in last-year students in the same field of study.

The proposed general objectives are:

1. To determine if the sketching of architectural spaces in immersive 3D virtual environments using virtual reality glasses improves spatial skills.

2. To confirm if the user immersion in architectural spaces artificially created in virtual reality environments allows for spatial perception and sensorial awareness as if they were performed in real spaces.

In order to verify these objectives, the following hypotheses will be addressed:

1. H1A: First-year architecture students improve the components of spatial skills (mental rotation, visualization and orientation) after being trained in the sketching of architectural spaces in immersive VR spaces.
2. H2A: First-year architecture students improve their spatial perception after being trained in the sketching of architectural spaces in immersive VR spaces.
3. H3A: Immersive spatial reality environments allow for the capturing of user sensations by visualizing and virtually interacting with architectural spaces.

For this purpose, a pilot study has been developed with first-year architecture students at the University of La Laguna in Spain and with students in the fifth and final year in similar degrees at the National University of San Agustín in Arequipa, Peru.

3. Methodology

For this research, a double experiment was carried out. The first one, directed specifically at first-year architecture students, created a series of training-oriented tasks for the development of spatial skills and required them to create three-dimensional drawings in an immersive virtual environment using head mounted displays. The second one, directed specifically at final-year students in the same degree, required them to visit a series of virtual architectural spaces in an immersive virtual reality environment using head mounted displays, where they were able to experience these spaces and register their perceptions and sensations while being inside them.

3.1. Measuring Instruments

As a consequence of the different lines of research in the field of psychology, numerous instruments have been developed to measure and evaluate the different components of spatial skills [28]. The instruments that were chosen to measure each of the components included in this research (see Figure 1) were the Mental Rotation Test (MRT) to measure mental rotation, the Differential Aptitude Test (DAT-5) to measure spatial visualization, the Perspective Taking/Spatial Orientation Test (SOT) to measure spatial orientation.

In order to detect possible problems related to visuoconstructive skills and visual memory in the participants, the Rey–Osterrieth Complex Figure Test (ROCFT) was administered. This test is carried out to have a neuropsychological evaluation that allows to jointly evaluate different functions such as visuospatial capacities, memory, attention, planning, working memory and executive functions.

All these measurement instruments are standardized and are the most widely used in international research.

The Mental Rotation Test (MRT) created by Stephen Vandenberg [50] contains 20 items in which the individual taking the test has a block figure in three-dimensional perspective. They are then shown four block figures with a different orientation, from which they must choose two that correspond to the model block (see Figure 3). The maximum score on this instrument is 40 points.

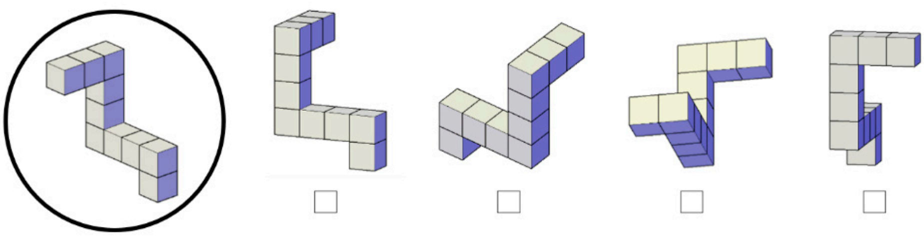


Figure 3. Example item in the Mental Rotation Test (MRT).

The Differential Aptitude Test: Spatial Rotation Subset (DAT-5) created by George K. Bennet and Alexander G. Wesman [51] consists of 50 items that present a model or pattern and to the right of each model are four three-dimensional figures. The student must determine from the original figure which is the only one that is able to be formed from the model (see Figure 4). One point is given per correct answer, and the maximum score is 50 points.

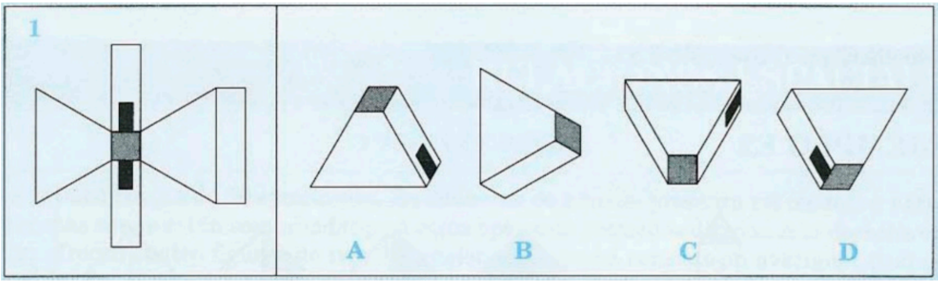


Figure 4. Example item in the Differential Aptitude Test: Spatial Rotation Subset (DAT-5).

The Perspective Taking/Spatial Orientation Test (SOT) created by Hegarty and Waller [52] consists of 12 items in which the user must imagine themself located in the position of one of the objects in a set (which will become the center of the circle) looking at another item (which will become the top of the circle). In response, they must draw an arrow from the center object indicating the direction to a third object from the new orientation (see Figure 5). The score of each item is the absolute deviation in sexagesimal degrees between the individual's answer and the correct answer, so that a lower score in the test results in a higher score. The ability to orient oneself in an environment and to imagine how it looks from different viewpoints requires different skills than does being adept at spatial transformations of individual objects [53] (spatial visualization).

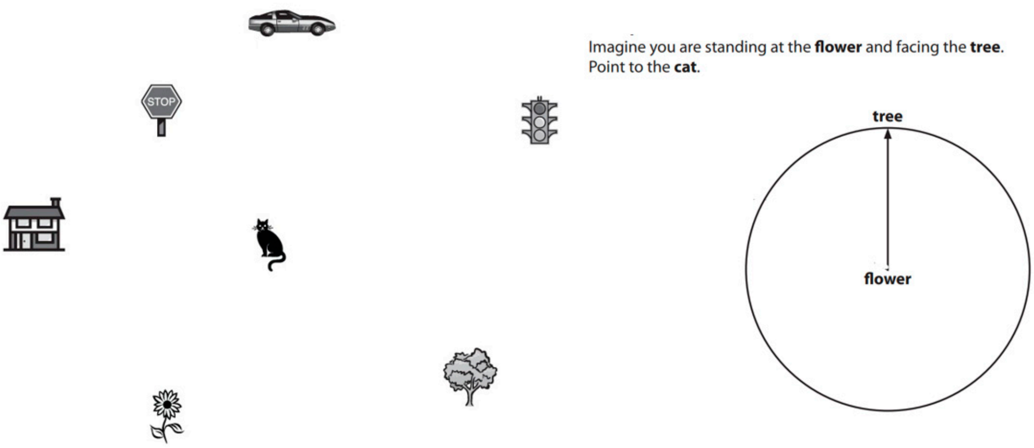


Figure 5. Example item in the Perspective Taking/Spatial Orientation Test (SOT).

The Rey–Osterrieth Complex Figure Test (ROCFT) created by Rey and Osterrieth [54] consists of drawing an exact copy of the drawing shown in Figure 6, which is always in view. Once the user has finished drawing and after a lapse of three minutes the user must draw the same image again, but this time without seeing the original object. This test has no time limit, and 18 aspects are evaluated with two points each, so the maximum score is 36. Several studies collect normative/standard data on non-clinical sample neuropsychological measures [55–58].

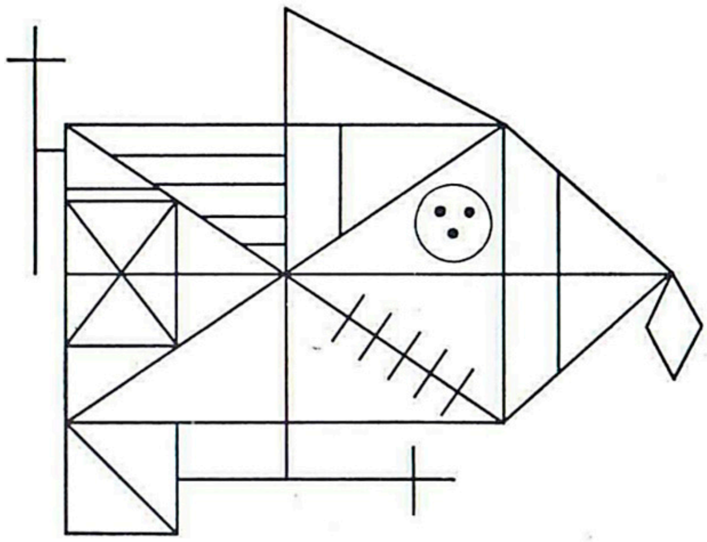


Figure 6. An abstract drawing replica in the Rey–Osterrieth Complex Figure Test (ROCFT).

Studying emotions is a complex and subjective phenomenon. Recently psychologists and neuroscientists have deepened their quantitative understanding of bodily reactions using advanced biosensors [59]. Nevertheless, these studies are unable to provide guidelines and practical criteria so that architects and designers are able to incorporate emotions in their designs. This reductionist approach to understanding the impact of architecture on emotions fails to address the complex and multisensory nature of the architectural experience [60]. This body of literature merely indicates that in order to improve the measurement of emotions it is necessary to combine objective and subjective tests (surveys or interviews).

For the measurement of the perceptual experience in the virtual world, an ad-hoc survey was created for this study. It consists of 10 questions in which the participant expressed their sensations about five dimensions that the virtually built space showed: scale and size, construction materials, architectural style, use, and domain (Table 1).

Table 1. Table of perception of sensations.

Categories	Sensations		
1. Scale and size	(a) Restlessness	(b) Balance	(c) Grandeur
2. Materials	(a) Warmth/Comfort	(b) Fragility/Exposure	(c) Distance/Frigitity
3. Architectural style	(a) Elegance/Satisfaction	(b) Simplicity/Serenity	(c) Eccentrism/Surprise
4. Use and related activity	(a) Joy/Theatricality	(b) Sadness/Nostalgia	(c) Emotion/Spirituality
5. Degree of enclosure	(a) Protection	(b) Calmness	(c) Freedom

3.2. Training Design Based on Architectural Spaces to Draw and Perceive

For the first part of this research, six modules of ephemeral architecture (small architectural spaces) were designed. Each was grouped into three levels of difficulty according to their complexity. Students were presented with graphic representations of each space in paper format: top, front and side views as well as three conic perspectives with a person drawn inside so they could analyze and observe them in detail (Figure 7). Then, the students were placed in an immersive virtual environment where the same images were also available. With this additional help and by using the drawing tools of Tilt Brush, the

Google application proposed for the training (https://www.tiltbrush.com), they were able to draw the proposed space in life-size proportions.

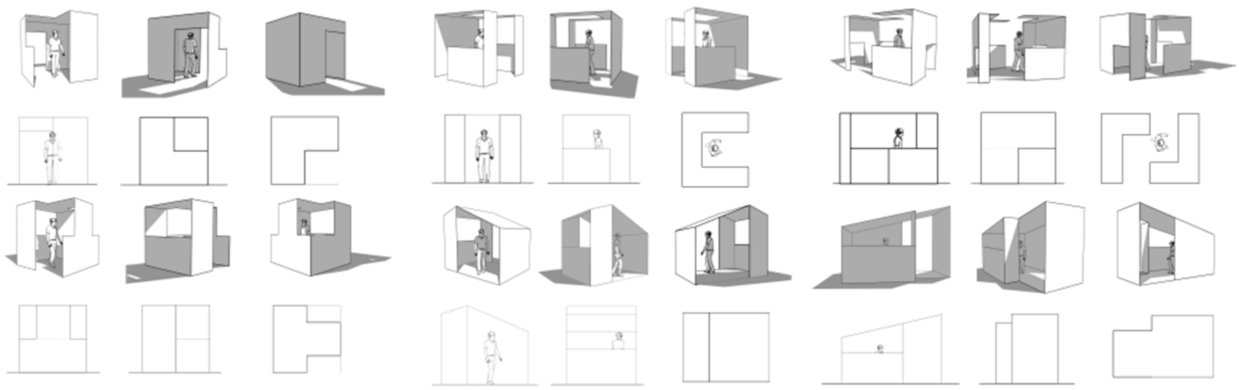


Figure 7. Architectural spaces to be drawn using immersive virtual reality.

For the second part of the experimentation, the same set of six architectural spaces was used, but on this occasion the three-dimensional virtual models were created with SketchUp pro 2019, where various materials, textures, colors and natural lighting were assigned (Figure 8). Then, the Enscape 3D virtual reality application (https://enscape3d.com) was used for their respective visualization. Finally, each student, with the use of the HMDs, underwent a virtual tour of each one of the spaces while having their perceptions and sensations recorded.

Figure 8. Architectural spaces to be perceived using immersive virtual reality.

4. The Experimental Study

In order to evaluate the two objectives of this research, the experimental study was carried out with architecture students from two universities: first-year students at the University of La Laguna in Spain and final-year students at the National University of San Agustín in Peru.

4.1. Participants

The participants in this research were students enrolled in the first course of the Architecture degree program at the University of La Laguna (ULL) in Spain. They participated in the experiment to verify the first objective of this research, which is related to the improvement of spatial skills as a result of specific training in 3D sketching in immersive VR environments. Additionally, students enrolled in the final course in the same degree plan from the Universidad Nacional de San Agustín de Arequipa (UNSA) in Peru, participated in the second experiment of this study. They verified the second objective of the research related to the experimentation of sensory and experiential perception of architectural spaces built in virtual environments.

In both cases, students were voluntarily recruited to participate in this pilot study. In the ULL experience the training group consisted of 14 individuals, aged between 18 and 20 years old, while the control group made up of 16 individuals, aged between 18 and 20 years old, did not perform the training experiment; none of the students of the two groups that participated in the experiment had previous training in spatial skills or virtual reality management. In the UNSA experience, the experimental group consisted of 11 participants, aged between 21 and 27, and none of them had previous training in spatial skills or virtual reality management.

4.2. Equipment

The hardware used for the training of spatial skills improvement by drawing in an immersive virtual environment consisted of a laptop HP OMEN 15-dc1015ns Core i7 9750H/2.6 GHz—6 cores Win 10 Home 64 bit 16 GB RAM to which the HTC VIVE Cosmos VR Headset was connected. The laptop was connected to a large format monitor so that the moderator could see how the participant was doing the experiment within the virtual environment. The software application used to draw was Tilt Brush, a commercial application developed by Google, as previously mentioned.

The hardware used to gather the participants' perceptions and sensations when experiencing the given spaces in an immersive virtual environment consisted of a PC, with 8 Gb of RAM, to which the Oculus Rift VR Headset was connected. The architectural spaces were modeled in SketchUp Pro 2019 and visualized in the VR Enscape 3D version 2.6 app.

4.3. Study Description

4.3.1. Training for the Improvement of Spatial Skills

The first contact with all the participants of the experimental group and the control group was made in order to administer the measurement tests. The MRT and DAT tests were administered one day, and they were scheduled to return the following day to administer the SOT and ROCFT measurement tests. The experimental group was informed of the dates and times they would individually have to start the training sessions. Each participant was assigned a specific time and day to practice and become familiar with the immersive virtual reality environment, the HMD, and the Tilt Brush application for freehand 3D drawing. In addition, they were assigned a specific time and day for three sessions on different days that they would have to attend for the training.

Each session lasted a maximum of 45 min and was conducted individually with each of the participants. In each session, the participant, using the HMD, drew in free-form two proposed architectural spaces in three dimensions. This occurred in such a way that in three sessions six spaces were drawn (two basic, two intermediate and two advanced) (see Figure 9). The three sessions were held on alternate days in the same week. Once all the participants had completed the three sessions and therefore completed the training, both the experimental and control groups, were again called to administer the tests, except ROCFT. In order to compare and confirm if there were significant differences, pre and post-test data were obtained from the group that performed an activity related to visuospatial mental processes and a group that did not perform such activities.

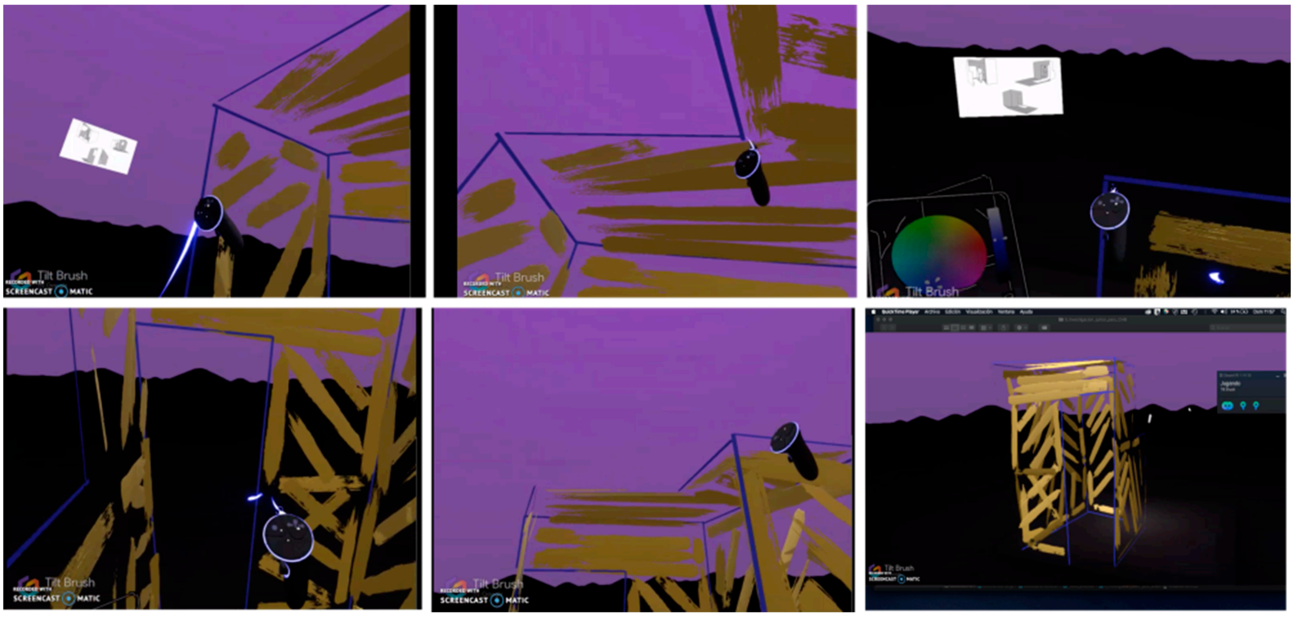


Figure 9. Scenes drawing with Tilt-Brush.

4.3.2. Perceptive Experience in the Virtual World

The initial contact was made with all the participants to obtain their general information and to inform them of the dates and times they would have to individually attend the experiment. Only one 45-min session was required for each participant. The first 15 min were used to practice and become familiar with the HMD, the immersive virtual reality environment and the haptic (handheld) controllers to be able to move in the virtual space. Once inside the virtual environment, for a period between 20 and 25 min, the participant had the possibility to take an immersive virtual tour of an open space where the six ephemeral architecture modules were located. The participant autonomously walked along the pedestrian path, being able to look all around, bend over, turn around and be transported directly to some point in order to observe both the space inside and outside, as well as the materials, shapes and dimensions (Figures 10–12).

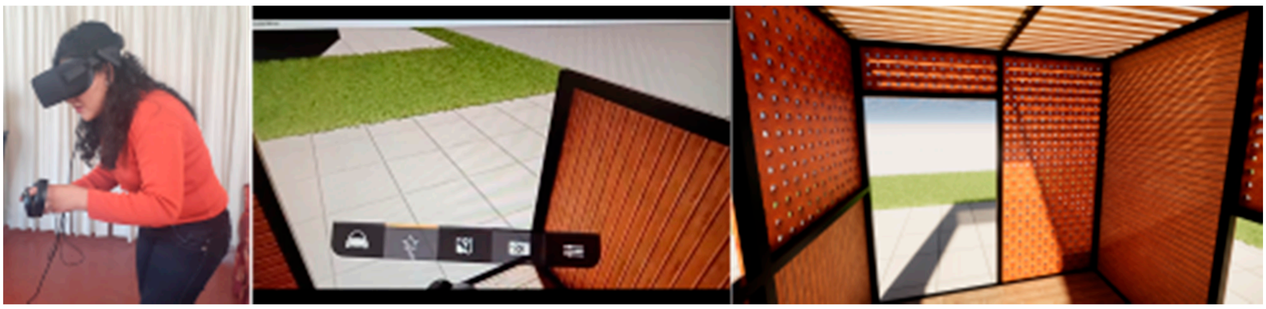


Figure 10. Immersion in architectural spaces.

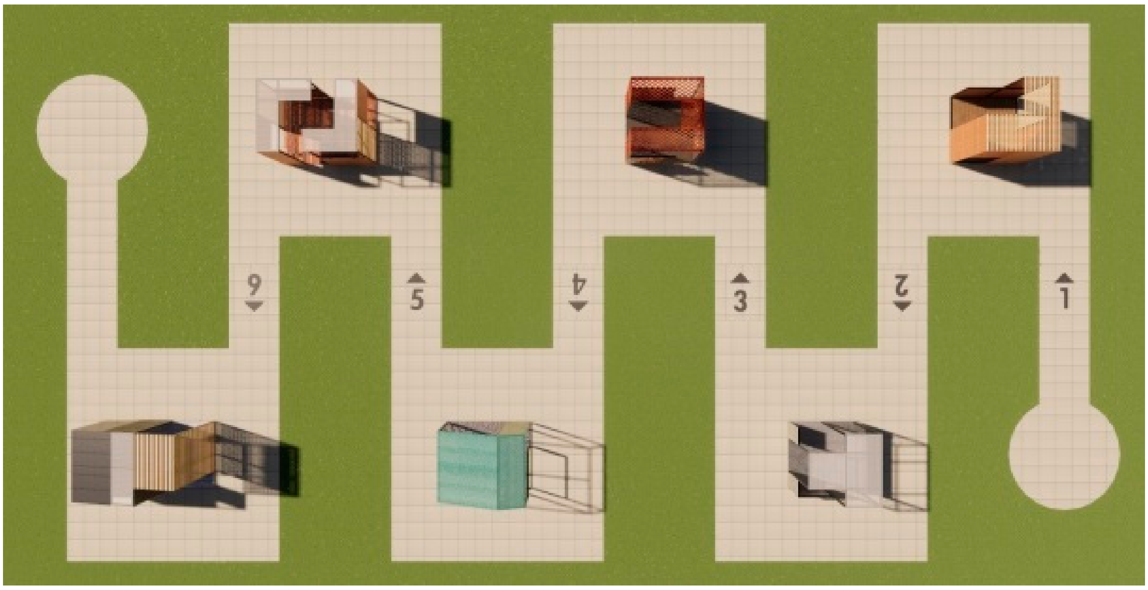


Figure 11. Tour of architectural spaces.

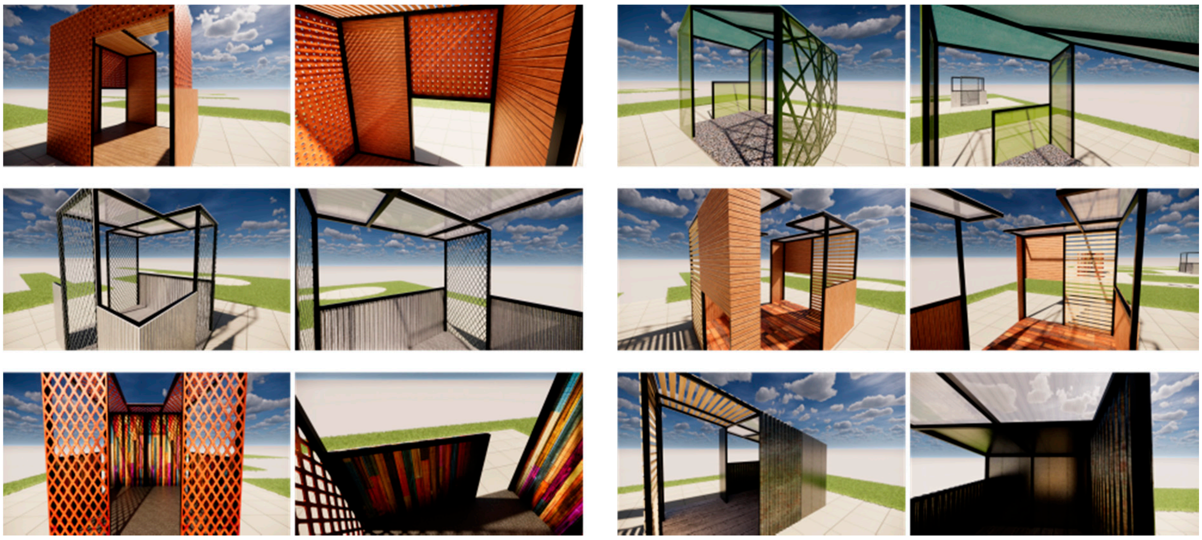


Figure 12. Artificially created architectural spaces in virtual reality environments used for the exercise of identifying sensations.

Once inside each space, the participant was offered to sit in a real chair to better experience the space and answer the questions of the ad-hoc survey, which was created to obtain information about their perceptions and sensations. The participant was then asked to choose one sensation from a set of three in the scale and size category, then one from the set of three in the materials category, and so on, until five sensations were chosen, one from each category (see Table 1). Finally, the participant was asked to mention two sensations that, according to their own perception, were the most representative of each space.

5. Results

5.1. Results and Analysis of Spatial Skills in ULL

To know the effect produced by the training in the experimental group, the gain acquired in each of the instruments that measure the components of the spatial skills is compared with the gain acquired by the control group. In this study, the independent variable was the groups, and the dependent variable was the gain of each of the components.

Table 2 displays the statistical description of data that was compiled for each of the groups.

Table 2. Statistical description of data.

	MRT Mean Value (SD)		DAT-5 Mean Value (SD)		SOT Mean Value (SD)		ROCFT Mean Value (SD)
	PRE	POST	PRE	POST	PRE	POST	
Experimental group ***n*= 14**	17.21 (8.30)	23.29 (11.02)	29.29 (10.67)	36.29 (9.10)	46.52 (26.97)	28.03 (19.40)	27.00 (5.85)
Control group ***n*= 16**	20.06 (10.81)	22.25 (9.57)	28.25 (9.64)	32.06 (8.50)	43.49 (27.08)	26.42 (28.37)	23.00 (4.98)

First, it is verified that the data collected before training follows a normal distribution. In order to do the statistical analysis, it was necessary to establish the fact if the experimental groups and control groups were homogeneous in terms of their spatial skills.

The Shapiro–Wilk test (used on samples of less than 50 people) were used to test the normality of each sample. This test was run on data pretest from MRT, DAT-5SR, SOT and ROCFT from each group (experimental and control).

Table 3 summarizes the results of the normality distribution analysis of the study samples. The results of the normality tests for both groups indicate that in all cases the data are distributed according to the normal.

Table 3. Normality test for samples from both groups (experimental group and control group).

	Group	Shapiro–Wilk		
		F	**gl**	**Sig.**
MRT	Experimental	0.901	14	0.115
	Control	0.968	16	0.825
DAT5-SR	Experimental	0.949	14	0.548
	Control	0.932	16	0.263
SOT	Experimental	0.945	14	0.479
	Control	0.885	16	0.052
ROCFT	Experimental	0.884	14	0.055
	Control	0.950	16	0.528

On the other hand, the mean values obtained in the Rey–Osterrieth complex figure test indicate that the participants in both groups (experimental and control) do not have any neurological/clinical problem that prevents them from training and improving the components of spatial ability. The values are aligned with normalized values [55–58].

At this stage of analysis, the research team checked whether there is a significant difference in the level of spatial awareness between the two groups prior to receiving training. A Student's *t*-test on independent samples produced p-value > 0.05 for the components of spatial ability (see Table 4). This means that in the three components of spatial ability that have been measured there is no significant difference between experimental and control groups before training, in other words both groups have the same level of spatial ability before training.

Table 4. p-Values prior training in each of the components of Spatial Skills.

	Pre MRT	Pre DAT-5	Pre SOT
Control Group vs. Experimental Group	$p = 0.43$	$p = 0.78$	$p = 0.89$

The objective of this study was to assess whether the students made any gains in spatial ability components after undergoing training based on drawing using full-scale 3D sketching techniques in VR environments.

In a controlled experiment, students' abilities were measured prior to and following the proposed experiment. The control group did not perform any training. The mean value of the gain in results of the pre and posttest of the experimental group and control group are displayed at Table 5.

Table 5. Gain in scores for each of the spatial ability components.

	Gain MRT Mean Value (SD)	Gain DAT-5 Mean Value (SD)	Gain SOT * Mean Value (SD)
Experimental group $n = 14$	6.07 (4.14)	7 −4.62	29.72 −41.72
Control group $n = 16$	2.19 −3.94	3.81 −3.71	46.4 −24.38

* Percentage decrease. It is the value to be taken into account as a gain. (it is better if the percentage is lower).

The research team proceeded to explore whether there are significant differences between the control group and the experimental group at the Universidad de La Laguna after training.

The following research hypotheses were defined to verify the improvement of spatial skills on students at Universidad de La Laguna:

HR1: the experimental group demonstrates an improvement in spatial visualization measured with the DAT5- following the proposed training experiment.

HR2: the experimental group demonstrates an improvement in spatial relation measured with the MRT following the proposed training experiment.

HR3: the experimental group demonstrates an improvement in spatial orientation measured with the SOT test following the proposed training experiment.

The T-student statistic was applied to compare the average gain values of each of the mean components between the two groups. It was obtained p-value = 0.01 for MRT gain, p-value = 0.04 for DAT-5 gain and p-value = 0.039 for SOT.

In each case, the measurement of the components yields a p-value less than 0.05, which means that there is a significant difference in the improvement of mental rotation, visualization, orientation and spatial perception. It can be stated that the experimental group has achieved greater gains in the measurements after training than the control group, and the research hypotheses HR1, HR2 and HR3 were all accepted.

5.2. Results of Spatial Perception in UNSA

As previously mentioned, the ephemeral architecture has taken a huge dimension in the world of design in recent years. The architect is not only concerned with making designs and representations of attractive spaces but must also appeal in its designs to the senses and emotions through forms and materiality, always seeking maximum expressiveness with a minimum of space.

The architect is not only concerned with designs and representations of attractive spaces but must also consider in their designs the senses and emotions that users may feel through the shapes and materiality, always seeking maximum expressiveness with a minimum of space.

The graphs in Figure 13 identify the sensations perceived by the participants in each of the six spaces when experiencing them in an immersive virtual reality environment. In each column of the graphs, each of the five dimensions of the instrument discussed in Section 3.1, Table 1, is analyzed.

Table 6 shows the sensations that the designer expects the users to perceive from their designs and the real sensations that the participants perceived when experiencing and walking through such spaces in an immersive virtual reality environment. The percentage indicates the degree of agreement of the user with the designer. The average degree of coincidence considering the six spaces evaluated reaches 72.29%.

Table 7 shows the two sensations that the participants considered the most representative and intense of each space.

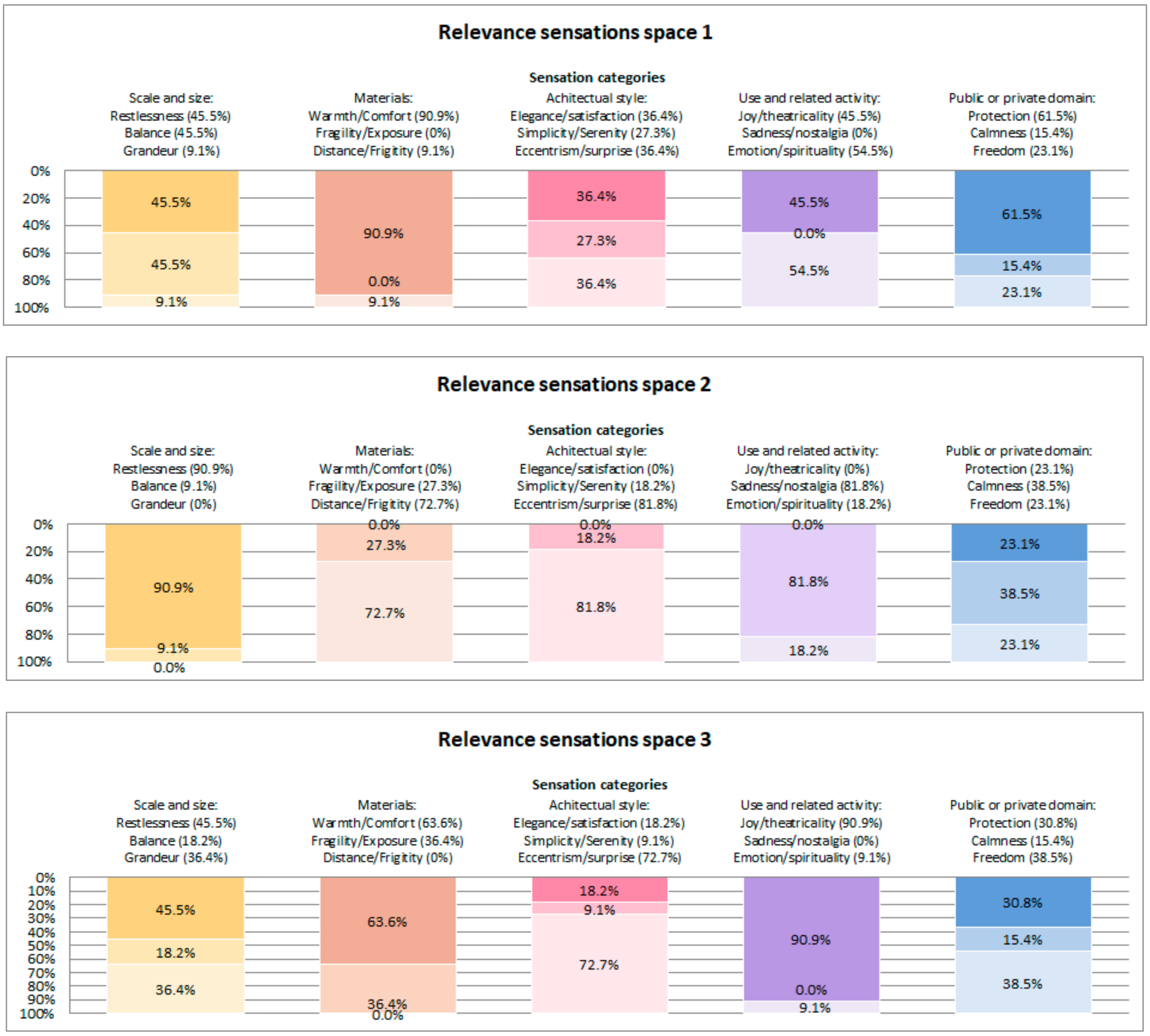


Figure 13. *Cont*.

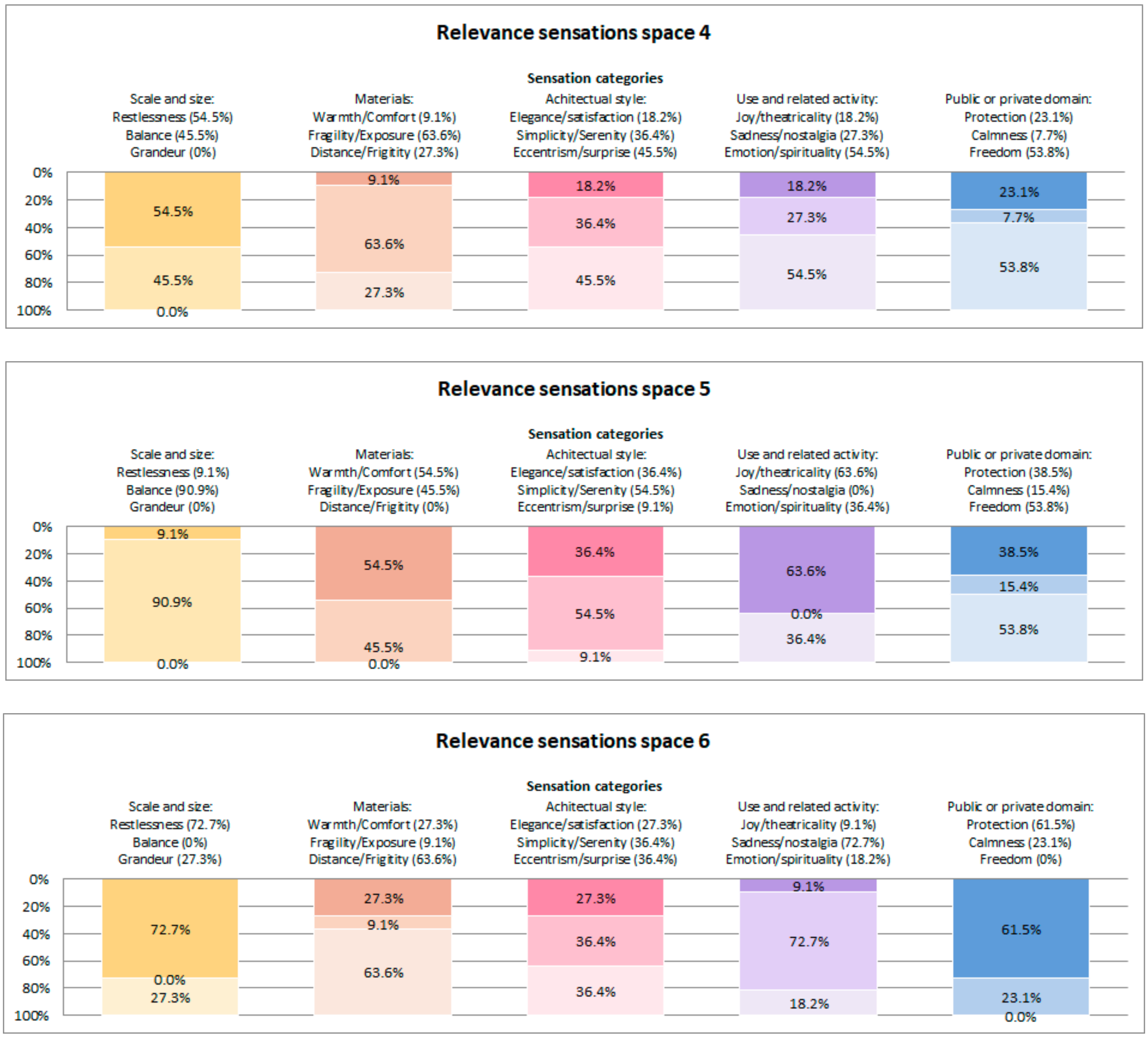


Figure 13. Sensations perceived by the participants in each of the spaces.

Table 6. Proposed and predominant sensations.

Space	Sensations Proposed by Designer	Predominant Sensations That Participants Felt
1. 	Warmth-comfort Protection	Warmth-comfort 90.9% Protection 61.5%
2. 	Sadness-nostalgia Distance-Frigidity	Restlessness 90.9% Sadness-nostalgia 81.8% Eccentrism-surprise 81.8%

Table 6. *Cont.*

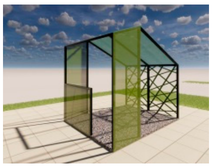
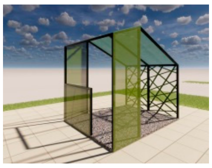
Space	Sensations Proposed by Designer	Predominant Sensations That Participants Felt
3. 	Joy-theatricality Eccentrism-surprise	Joy-theatricality 90.9% Eccentrism-surprise 72.7%
4. 	Fragility-Exposure Freedom	Fragility-Exposure 63.6% Emotion-spirituality 54.5% Restlessness 54.5%
5. 	Balance Simplicity-Serenity	Balance 90.9% Joy-theatricality 63.6% Simplicity-Serenity 54.5%
6. 	Sadness-nostalgia Protection	Restlessness 72.7% Sadness-nostalgia 72.7%

Table 7. Most representative perceived sensations.

Space	Most Representative Perceived Sensations Declared by Participants
1. 	Warmth-comfort 22.73% Protection 22.73%
2. 	Restlessness 27.27% Distance-Frigidity 27.27% Fragility-Exposure 13.64% Sadness-nostalgia 13.64%
3. 	Joy-theatricality 36.36% Eccentrism-surprise 22.73%

Table 7. *Cont.*

Space	Most Representative Perceived Sensations Declared by Participants
4. 	Fragility-Exposure 22.73% Distance-Frigidity 13.64% Emotion-spirituality 13.64% Restlessness 13.64%
5. 	Freedom 22.73% Warmth-comfort 18.18% Protection 18.18% Fragility-Exposure 18.18%
6. 	Sadness-nostalgia 22.73% Protection 22.73%

6. Discussion

The first part of this research has sought to determine the effects of short training sessions using immersive virtual reality to improve spatial skills by differentiating three components: spatial rotation, spatial visualization and spatial orientation. Based on the results, it has been determined that there is a positive effect on the improvement of spatial skills in each one of its dimensions. Most of the authors consider the spatial orientation component as part of rotation and spatial visualization, so they do not consider it a specific and independent component. In this research, we tried to find a difference in the spatial orientation with respect to the others, since in the proposed training tasks took into account working with architectural spaces at real scales, which demanded navigation capabilities and orientation in walkarounds much more related to that spatial orientation component. However, this difference has not yet been found, which suggests that it should be followed this tendence of specific analysis of spatial orientation in trainings related to geographic and cartographic tasks [30,31,61,62].

We consider that this study serves as a clarifying contribution so that the analyses of spatial skills improvement can follow the proposal of Carroll [13] and backed by numerous authors [27,28,63] who propose two components for spatial skills: spatial relations, which contain the spatial orientation, and spatial visualization.

In the second part of the study, six architectural spaces have been designed to generate different sensations in users, with at least two with greater intensity and clarity. By experiencing the life-size spaces in immersive virtual reality, students reported having perceived the same sensations with a very high coincidence, up to 72,29%, e.g., the sensations experienced by the participants coincide by 72.29% with those indicated by the designers (considering the ideal case that the designers agree 100% on the two predominant sensations per space). This is due to the sense of presence (subjective feeling of being present elsewhere) that is determined in virtual environments by immersion and realism, which has been an important concept in understanding and evaluating the effectiveness of virtual environments primarily in the context of human experience [64,65] and the perception of architectural spaces. Although the ideal measurement of sensations is the combination of objective tests through biosensors and subjective tests through questionnaires or surveys [59], in this study we have only used the last ones to complement them with sensors in future research.

As for the categories of sensations proposed, it has been observed that the sensations for the category of use and activity (joy/theatricality, sadness/nostalgia and emotion/spirituality), provoked greater coincidences, that is to say, the experience inside and outside virtual spaces has allowed users to feel and imagine what activities they could carry out in those spaces. This is essential in order to evaluate the spaces before they are occupied and to additionally check whether the final utility of an architectural space has been achieved before its actual construction by providing qualitative information on the performance of the buildings [66,67].

The sensations caused by the category of materials (warmth/comfort, fragility/exposure and distance/indifference) were expected to be the ones with the most coincidences; however, it was the second one behind use and activity. The realism of the materials used in the virtual environment is an ever-present feature of immersive virtual reality, but the texture to the touch is a huge weakness since modifying haptic impressions in VR remains a challenge [68] and for now a disadvantage that distances it from the sensations that the materials cause in the real world. This may explain why the sensations caused by the materials have not been the most coincidental, but at the same time, it is a challenge because users want the full experience of spatial perception like "touching" the elements of space, interacting or feeling the real physical properties and effects of the elements.

7. Conclusions

There are many studies that have developed training programs aimed at the improvement of spatial skills and supported by different technological tools in engineering students, however, there is not much evidence of experiences that have used immersive virtual reality and three-dimensional drawing of architectural spaces to achieve positive effects in three components of spatial skills: spatial visualization, spatial rotation and spatial orientation. In this research the experimental group has achieved a significant improvement of the three mentioned components, which are important in the field of architecture. No significant difference has been found that allows us to conclude that spatial orientation has been improved by the training in which navigation and walkarounds were required and that it could be of help to architecture students who manage spaces to be inhabited, experienced and walked.

On the other hand, the walk arounds and sensory experimentation in architectural spaces realistically modeled in immersive virtual reality environments allows for the same sensations that the designer initially sought to convey. We are able to make this conclusion based on the coincidences expressed by the students when interacting with the six spaces in an immersive virtual environment. This second conclusion is also useful for learning architectural design since it is essential to determine before building, if the designs will meet the sensory expectations initially set by the architect, which will later determine the appropriate use of these spaces.

In immersive virtual reality environments, as it happens in the real world, the perception of the physical characteristics of an architectural space, such as dimensions, materials and degrees of enclosure, generate sensations that allow us to perceive a specific use and activity for that space, which is supported by the relationship between the space and the user who perceives it. This conclusion will allow us to investigate in the future, as is already being done [69], which characteristics or specific physical elements generate specific sensations, so that the student of architecture will be trained in this important aspect of their education.

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P.B.-E.; Writing—review and editing, H.C.G.-T., J.B.-E., P.B.-E. and J.M.-G. All authors have read and agreed to the published version of the manuscript.

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References

1. Sandnes, F.E. Sketching 3D Immersed Experiences Rapidly by Hand Through 2D Cross Sections. In *Online Engineering & Internet of Things*; Auer, M.E., Zutin, D.G., Eds.; Springer International Publishing: Cham, Switzerland, 2018; Volume 22, pp. 1001–1013. ISBN 978-3-319-64351-9.
2. Kvan, T.; Wong, J.T.; Vera, A.H. The Contribution of Structural Activities to Successful Design. *Int. J. Comput. Appl. Technol.* **2003**, *16*, 122–126. [CrossRef]
3. Israel, J.H.; Wiese, E.; Mateescu, M.; Zöllner, C.; Stark, R. Investigating Three-Dimensional Sketching for Early Conceptual Design—Results from Expert Discussions and User Studies. *Comput. Graph.* **2009**, *33*, 462–473. [CrossRef]
4. Tsou, C.-H.; Hsu, T.-W.; Lin, C.-H.; Tsai, M.-H.; Hsu, P.-H.; Lin, I.-C.; Wang, Y.-S.; Lin, W.-C.; Chuang, J.-H. Immersive VR Environment for Architectural Design Education. In *Proceedings of the SA '17: SIGGRAPH Asia 2017 Posters*; ACM Press: New York, NY, USA, 2017; pp. 1–2.
5. Hermund, A.; Klint, L.S.; Bundgaard, T.S. The Perception of Architectural Space in Reality, in Virtual Reality, and through Plan and Section Drawings. In Proceedings of the Computing for a better tomorrow, Lods, Poland, 19–21 September 2018; Volume 2, pp. 735–744.
6. Gomes, R.; Aquilué, I.; Roca, E. Cuerpo, espacio y el dibujo arquitectónico. *ACE Archit. City Environ.* **2017**, *12*. [CrossRef]
7. Tversky, B.; Suwa, M.; Agrawala, M.; Heiser, J.; Stolte, C.; Hanrahan, P.; Phan, D.; Klingner, J.; Daniel, M.-P.; Lee, P.; et al. Sketches for Design and Design of Sketches. In *Human Behaviour in Design: Individuals, Teams, Tools*; Lindemann, U., Ed.; Springer: Berlin/Heidelberg, Germany, 2003; pp. 79–86. ISBN 978-3-662-07811-2.
8. Lohman, D.F. Spatial ability and g. In *Human Abilities: Their Nature and Measurement*; Lawrence Erlbaum Associates, Inc.: Hillsdale, NJ, USA, 1996; pp. 97–116. ISBN 0-8058-1800-6.
9. Stumpf, H.; Eliot, J. A Structural Analysis of Visual Spatial Ability in Academically Talented Students. *Learn. Individ. Differ.* **1999**, *11*, 137–151. [CrossRef]
10. McGee, M.G. *Human Spatial Abilities: Psychometric Studies and Environmental, Genetic, Hormonal, and Neurological Influences*; American Psychological Association: Washington, DC, USA, 1979; Volume 86, ISBN 1939-1455(Electronic), 0033-2909(Print).
11. Schneider, W.J.; McGrew, K.S. The Cattell-Horn-Carroll model of intelligence. In *Contemporary Intellectual Assessment: Theories, Tests, and Issues*, 3rd ed.; The Guilford Press: New York, NY, USA, 2012; pp. 99–144. ISBN 978-1-60918-995-2.
12. Buckley, J.; Seery, N.; Canty, D. Spatial Cognition in Engineering Education: Developing a Spatial Ability Framework to Support the Translation of Theory into Practice. *Eur. J. Eng. Educ.* **2019**, *44*, 164–178. [CrossRef]
13. Carroll, J.B. *Human Cognitive Abilities. A Survey of Factor-Analytic Studies*; Cambridge University Press: New York, NY, USA, 1993.
14. Gómez-Tone, H.C. Impacto de La Enseñanza de La Geometría Descriptiva Usando Archivos 3D-PDF Como Entrenamiento de La Habilidad Espacial de Estudiantes de Ingeniería Civil En El Perú. *Form. Univ.* **2019**, *12*, 73–82. [CrossRef]
15. Tartre, L.A. Spatial Orientation Skill and Mathematical Problem Solving. *J. Res. Math. Educ.* **1990**, *21*, 216–229. [CrossRef]
16. Sorby, S.A. Developing 3-D Spatial Visualization Skills. *Eng. Des. Graph. J.* **1999**, *63*, 21–32.
17. Colby, C.L. Perception of Extrapersonal Space: Psychological and Neural Aspects. In *International Encyclopedia of the Social & Behavioral Sciences*; Elsevier: Amsterdam, The Netherlands, 2001.
18. Linn, M.C.; Petersen, A.C. Emergence and Characterization of Sex Differences in Spatial Ability: A Meta-Analysis. *Child. Dev.* **1985**, *56*, 1479–1498. [CrossRef]
19. Mitrache, A. Spatial Sensibility in Architectural Education. *Procedia Soc. Behav. Sci.* **2013**, *93*, 544–548. [CrossRef]
20. Akin, Ö.; Erem, Ö. Architecture Students' Spatial Reasoning with 3-D Shapes. *J. Des. Res.* **2011**, *9*, 339–359. [CrossRef]
21. Suh, J.; Cho, J.Y. Linking Spatial Ability, Spatial Strategies, and Spatial Creativity: A Step to Clarify the Fuzzy Relationship between Spatial Ability and Creativity. *Think. Ski. Creat.* **2020**, *35*, 100628. [CrossRef]
22. Wigfield, A.; Eccles, J.S.; Schiefele, U.; Roeser, R.W.; Davis-Kean, P. Development of Achievement Motivation. In *Handbook of Child Psychology*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2007.

23. Zimmerman, B.J.; Martinez-Pons, M. Student Differences in Self-Regulated Learning: Relating Grade, Sex, and Giftedness to Self-Efficacy and Strategy Use. *J. Educ. Psychol.* **1990**, *82*, 51–59. [CrossRef]
24. Burton, L.J.; Dowling, D.G. Key Factors That Influence Engineering Students' Academic Success: A Longitudinal Study. In *Proceedings of the Research in Engineering Education Symposium (REES 2009)*; University of Melbourne: Parkville, VIC, Australia, 2009; pp. 1–6.
25. Potter, C.; Van Der Merwe, E.; Kaufman, W.; Delacour, J. A Longitudinal Evaluative Study of Student Difficulties with Engineering Graphics. *Eur. J. Eng. Educ.* **2006**, *31*, 201–214. [CrossRef]
26. Sutton, K.; Williams, A.; Tremain, D.; Kilgour, P. University Entry Score Is It a Consideration for Spatial Performance in Architecture Design Students? *J. Eng. Des. Technol.* **2016**, *14*, 328–342. [CrossRef]
27. Connolly, P.; Sadowski, M. Measuring and Enhancing Spatial Visualization in Engineering Technology Students. *Age* **2009**, *14*, 1.
28. Martín-Gutiérrez, J.; Luís Saorín, J.; Contero, M.; Alcañiz, M.; Pérez-López, D.C.; Ortega, M. Design and Validation of an Augmented Book for Spatial Abilities Development in Engineering Students. *Comput. Graph.* **2010**, *34*, 77–91. [CrossRef]
29. Sorby, S.A. Educational Research in Developing 3-D Spatial Skills for Engineering Students. *Int. J. Sci. Educ.* **2009**, *31*, 459–480. [CrossRef]
30. Hegarty, M.; Montello, D.R.; Richardson, A.E.; Ishikawa, T.; Lovelace, K. Spatial Abilities at Different Scales: Individual Differences in Aptitude-Test Performance and Spatial-Layout Learning. *Intelligence* **2006**, *34*, 151–176. [CrossRef]
31. Montello, D.R.; Lovelace, K.L.; Golledge, R.G.; Self, C.M. Sex-Related Differences and Similarities in Geographic and Environmental Spatial Abilities. *Ann. Assoc. Am. Geogr.* **1999**, *89*, 515–534. [CrossRef]
32. Gómez-Tone, H.C.; Martin-Gutierrez, J.; Valencia Anci, L.; Mora Luis, C.E. International Comparative Pilot Study of Spatial Skill Development in Engineering Students through Autonomous Augmented Reality-Based Training. *Symmetry* **2020**, *12*, 1401. [CrossRef]
33. Roca-González, C.; Martin-Gutierrez, J.; García-Dominguez, M.; Carrodeguas, M. del C.M. Virtual Technologies to Develop Visual-Spatial Ability in Engineering Students. *Eurasia J. Math. Sci. Technol. Educ.* **2017**, *13*, 441–468. [CrossRef]
34. Kaufmann, H.; Schmalstieg, D.; Wagner, M. Construct3D: A Virtual Reality Application for Mathematics and Geometry Education. *Educ. Inf. Technol.* **2000**, *5*, 263–276. [CrossRef]
35. Dahmani, L.; Ledoux, A.A.; Boyer, P.; Bohbot, V.D. Wayfinding: The Effects of Large Displays and 3-D Perception. *Behav. Res. Methods* **2012**, *44*, 447–454. [CrossRef] [PubMed]
36. Darken, R.P.; Goerger, S.R. The Transfer of Strategies from Virtual to Real Environments: An Explanation for Performance Differences? *Simul. Ser.* **1999**, *31*, 159–164.
37. Lin, C.-H.; Chen, C.-M.; Lou, Y.-C. Developing Spatial Orientation and Spatial Memory with a Treasure Hunting Game. *J. Educ. Technol. Soc.* **2014**, *17*, 79–92.
38. Navarro, I.; de Reina, O.; Rodiera, A.; Fonseca, D. Indoor Positioning Systems: 3D Virtual Model Visualization and Design Process of Their Assessment Using Mixed Methods: Case Study: World Heritatge Buildings and Spatial Skills for Architecture Students. In Proceedings of the 2016 11th Iberian Conference on Information Systems and Technologies (CISTI), Las Palmas, Spain, 15–18 June 2016; pp. 1–6.
39. Gerson, H.B.P.; Sorby, S.A.; Wysocki, A.; Baartmans, B.J. The Development and Assessment of Multimedia Software for Improving 3-D Spatial Visualization Skills. *Comput. Appl. Eng. Educ.* **2001**, *9*, 105–113. [CrossRef]
40. Martin Gutierrez, J.; Garcia Dominguez, M.; Roca Gonzalez, C. Using 3D Virtual Technologies to Train Spatial Skills in Engineering. *Int. J. Eng. Educ.* **2015**, *31*, 323–334.
41. Regian, J.W.; Shebilske, W.L.; Monk, J.M. Virtual Reality: An Instructional Medium for Visual-Spatial Tasks. *J. Commun.* **1992**, *42*, 136–149. [CrossRef]
42. Cho, J.Y. Three Areas of Research on Spatial Ability in the Architectural Design Domain. *J. Archit. Eng. Technol.* **2012**, *1*, 1. [CrossRef]
43. Schnabel, M.A. The immersive virtual environment design studio. In *Collaborative Design in Virtual Environments*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 177–191.
44. Milovanovic, J.; Moreau, G.; Siret, D.; Miguet, F. Virtual and Augmented Reality in Architectural Design and Education. In *Proceedings of the 17th International Conference*; CAAD Futures: Eindhoven, The Netherlands, 2017.
45. Sandeep, G.; Harish, P. Tools and Techniques for Conceptual Design in Virtual Reality Environment. *Manag. J. Future Eng. Technol.* **2017**, *12*, 8. [CrossRef]
46. Yang, E.K.; Lee, J.H. Cognitive Impact of Virtual Reality Sketching on Designers' Concept Generation. *Digit. Creat.* **2020**, 1–16. [CrossRef]
47. Roberts, G.; Holmes, N.; Alexander, N.; Boto, E.; Leggett, J.; Hill, R.M.; Shah, V.; Rea, M.; Vaughan, R.; Maguire, E.A.; et al. Towards OPM-MEG in a Virtual Reality Environment. *NeuroImage* **2019**, *199*, 408–417. [CrossRef] [PubMed]
48. Kuliga, S.F.; Thrash, T.; Dalton, R.C.; Hölscher, C. Virtual Reality as an Empirical Research Tool—Exploring User Experience in a Real Building and a Corresponding Virtual Model. *Comput. Environ. Urban. Syst.* **2015**, *54*, 363–375. [CrossRef]
49. Yeom, D.; Choi, J.-H.; Kang, S.-H. Investigation of the Physiological Differences in the Immersive Virtual Reality Environment and Real Indoor Environment: Focused on Skin Temperature and Thermal Sensation. *Build. Environ.* **2019**, *154*, 44–54. [CrossRef]
50. Vandenberg, S.G.; Kuse, A.R. Mental Rotations, a Group Test of Three-Dimensional Spatial Visualization. *Percept. Mot. Ski.* **1978**, *47*, 599–604. [CrossRef]

51. Bennett, G.K.; Seashore, H.G.; Wesman, A.G. *The Differential Aptitude Tests*; Spanish Of.; TEA Ediciones: New York, NY, USA, 1947; Volume 35.
52. Hegarty, M.; Waller, D. A Dissociation between Mental Rotation and Perspective-Taking Spatial Abilities. *Intelligence* **2004**, *32*, 175–191. [CrossRef]
53. Kozhevnikov, M.; Hegarty, M. A Dissociation between Object Manipulation Spatial Ability and Spatial Orientation Ability. *Mem. Cognit.* **2001**, *29*, 745–756. [CrossRef]
54. Osterrieth, P.A. Le Test de Copie d'une Figure Complexe; Contribution à l'étude de La Perception et de La Mémoire. [Test of Copying a Complex Figure; Contribution to the Study of Perception and Memory.]. *Arch. Psychol.* **1944**, *30*, 206–356.
55. Bornstein, R.A. Normative Data on Selected Neuropsychological Measures from a Nonclinical Sample. *J. Clin. Psychol.* **1985**, *41*, 651–659. [CrossRef]
56. Caffarra, P.; Vezzadini, G.; Dieci, F.; Zonato, F.; Venneri, A. Rey-Osterrieth Complex Figure: Normative Values in an Italian Population Sample. *Neurol. Sci.* **2002**, *22*, 443–447. [CrossRef] [PubMed]
57. Bertolani, L.; De Renzi, E.; Faglioni, P. Normative Data on Non-Verbal Memory Test of Clinical Interest. *Arch. Psicol. Neurol. Psichiatr.* **1993**, *54*, 477–486.
58. Ardila, A.; Rosselli, M.; Rosas, P. Neuropsychological Assessment in Illiterates: Visuospatial and Memory Abilities. *Brain Cogn.* **1989**, *11*, 147–166. [CrossRef]
59. Homolja, M.; Maghool, S.A.H.; Schnabel, M.A. The Impact of Moving through the Built Environment on Emotional and Neurophysiological State-A Systematic Literature Review. In Proceedings of the 25th CAADRIA Conference, Bangkok, Thailand, 5–6 August 2020.
60. Pallasmaa, J. *The Thinking Hand: Existential and Embodied Wisdom in Architecture*; Wiley Chichester: Chichester, UK, 2009; ISBN 0-470-77928-4.
61. Weisberg, S.M.; Newcombe, N.S. How Do (Some) People Make a Cognitive Map? Routes, Places, and Working Memory. *J. Exp. Psychol. Learn. Mem. Cogn.* **2016**, *42*, 768–785. [CrossRef] [PubMed]
62. Carbonell-Carrera, C.; Saorin, J.L.; Hess-Medler, S. Spatial Orientation Skill for Landscape Architecture Education and Professional Practice. *Land* **2020**, *9*, 161. [CrossRef]
63. Veurink, N.; Hamlin, A.J.; Sorby, S. Impact of Spatial Training on "Non-Rotators". In Proceedings of the 68th Mid-Year Conference, Worcester, MA, USA, 20–23 October 2013; pp. 15–22.
64. Ghani, I.; Rafi, A.; Woods, P. The Effect of Immersion towards Place Presence in Virtual Heritage Environments. *Pers. Ubiquitous Comput.* **2020**, *24*, 861–872. [CrossRef]
65. Alatta, R.A.; Freewan, A. Investigating the effect of employing immersive virtual environment on enhancing spatial perception within design process. *ArchNet-IJAR Int. J. Archit. Res.* **2017**, *11*, 219. [CrossRef]
66. Moloney, J.; Globa, A.; Wang, R.; Khoo, C. Principles for the Application of Mixed Reality as Pre-Occupancy Evaluation Tools (P-OET) at the Early Design Stages. *Archit. Sci. Rev.* **2019**, *63*, 441–450. [CrossRef]
67. Ergan, S.; Radwan, A.; Zou, Z.; Tseng, H.; Han, X. Quantifying Human Experience in Architectural Spaces with Integrated Virtual Reality and Body Sensor Networks. *J. Comput. Civ. Eng.* **2019**, *33*, 04018062. [CrossRef]
68. Degraen, D.; Zenner, A.; Krüger, A. Enhancing Texture Perception in Virtual Reality Using 3D-Printed Hair Structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*; ACM: New York, NY, USA, 2019.
69. Shemesh, A.; Talmon, R.; Karp, O.; Amir, I.; Bar, M.; Grobman, Y.J. Affective Response to Architecture–Investigating Human Reaction to Spaces with Different Geometry. *Archit. Sci. Rev.* **2017**, *60*, 116–125. [CrossRef]