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Using virtual reality environments to unveil the imageability of the city in homogenous and heterogeneous environments

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ABSTRACT

The presented work explores the way the information conveyed by the morphology of urban artifacts affects the way we perceive the built environment. The above exploration is implemented by means of Virtual Reality Environments we have specifically developed for this purpose. We compare heterogeneous environments characterized by a heavy tailed distribution with homogeneous environments that are characterized by normal distribution and show that the former provide higher level of information and thus better *imageability* than the latter.

1. Introduction

Cities are examples of complex, self-organizing systems (Batty and Longley, 1994; Portugali, 2000, 2011; Batty, 2005, 2011). This is due to the fact that they initially emerged and have been developing as a result of the interactions between numerous agents that are situated and act in space and time (Alexander, 1965; Salingaros, 2001), inspired by many objectives and motivations that are related to cognitive abilities, economic considerations, political ambitions, and so on. In recent years, the science of complex systems has developed to urban studies (among other fields) and thus, we are faced with new models that explore cities as complex networks. In many cases, the topologies of these networks obey power law distributions (Batty, 2005; Andersson et al., 2005; Andersson et al., 2006; Porta et al., 2006; Hu et al., 2006; Jiang and Claramunt, 2004, Jiang, 2013a,b). In this work, we focus on a unique quality that distinguishes cities from other complex systems, that is, human cognition and specifically spatial cognition which is one of the characteristics of humans who are basically the components of the city.

The study of spatial cognition goes back to the late 1940s when the psychologist Edward C. Tolman published his seminal work on *Cognitive Maps in Rats and Men* (1948), where he first coined the term "cognitive map". This term refers to the internal representation in the mind/brain of the external environment. "Cognitive maps" are actually pieces of information that, among other things, assist humans (and other animals) in their spatial navigation. The pioneering work that refers to perception of urban environments is Lynch's *Image of the City* (1960), where the author analyzed graphical and verbal representations of the urban environment, as described by the participants in his study. Lynch himself didn't refer to these representations as cognitive maps; however, based on his work, "The Image of the City" (1960) he was later considered as one of the first "mental mappers" (Downs and Stea, 1973). In his study, Lynch identified 5 major elements that are most influential on people's image of the city: paths, nodes, edges, districts, and landmarks. These elements are mostly based on the morphology of the built environment. Following Lynch, there has been extensive work on the relations between the built environment and the way we perceive it in our minds (Evans et al., 1984; Montello, 1991; Golledge, 1999; Devlin, 2001; Penn, 2003). Thus, Sadalla et al. (1980) showed that we use different elements as reference points to define the position of nearby places in large-scale areas. Sadalla and Montello (1989) proved that environments with orthogonal coordinates are better perceived than environments that are represented by different angles between their pathways.

Other studies have also explored the topological characteristics of different environments and their effect on our human behavior (see for example the theory of Space Syntax). Hillier and Iida (2005) showed that vehicular and pedestrian movement in urban environments is affected by the geometrical and topological characteristics of the environment more than by its metric properties. Haq and Girotto (2003) claimed that both geometric and metric relations are important measures in predicting way-finding and spatial perception, and thus both of them cannot be ignored. Employing Shannon's information theory (Shannon and Weaver, 1949), in conjunction with studies that applied Shannon's information to cognition, Haken and Portugali (2003) have demonstrated three major points: firstly, that different morphological

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elements in the urban landscape are perceived as transmitting different amounts of information (i.e. provide different informative levels in terms of their morphology). Secondly, that these amounts can be quantified using Shannon's information bits. Thirdly, that semantic information enters in disguise into the definition of Shannon's information. In so doing they have added a cognitive support to Lynch's (1960, 2–3) notion of legibility: due to their form, some urban elements convey more information than others in making a city "legible".

In this work we follow Haken and Portugali (2003) and explore the impact of different informative levels of urban morphology on the way we perceive the environment. We focus on the shapes of the buildings and the voids between them. Real environments are complex and provide morphological information that is mixed with other types of information such as age, style, or function of buildings. Thus, in order to isolate the morphological characteristics of the environment from its symbolic characteristics, we have decided to create a theoretical environment and use Virtual Reality Environment (VRE) to explore the impact of the morphology alone on the way we perceive an environment.

Virtual environments have long been used to simulate different aspects of spatial cognition and navigation (see for example Conroy-Dalton, 2001; Conroy-Dalton, 2002). Tlauka and Wilson (1996) showed that studying a new environment based on navigating in a virtual environment might present similar aspects to studying a new real environment. Wilson et al. (1997) showed that people can transfer information, gained from a virtual environment to the real environment. Doeller et al. (2008) found that navigation in virtual environments stimulates the hippocampus,[1] similarly to the way navigation in real environments does. Richardson and Montello (1999) claim that studying a new virtual environment is similar to studying the real environment as those who study the virtual environment explore it from a horizontal perspective and thus gradually, based on moving within it they build its representation. Peruch et al. (2000) also examined the ability of people to study a virtual environment and implement the knowledge gained from it in the real world. They found that the richer the virtual environment is — the better spatial representation it provides. However, it is possible to transfer spatial knowledge from virtual environment to the real world even when the virtual environment is schematic. Billinghurst and Weghorst (1995) discovered that there is good correlation between the sense of spatial orientation, reported by participants who navigated in virtual environments and the accuracy of the maps they drew of these environment. They concluded that such maps, also referred to as sketch maps (Kim, 2001), can be used as a reliable indicator to the internal representation of people who studied new virtual environments. However, there is a difficulty in quantifying the results gained from such maps, as their quality is dependent on drawing abilities and previous cartographic knowledge of the participants (Kitchin and Blades, 2002). Yet, despite the above shortcomings, using sketch-maps as a means to study spatial cognition in different environments have become an acceptable methodology in the field (see the works of Sadalla and Montello, 1989; Evans et al., 1980; Tversky, 1981, Haq & Zimring, 2003; Kim, 2001).

Based on the above, in this work, we used a virtual environment to simulate two settings where we can control the level of information available to the participants in our study. We compared the movement of the participants in both settings and the related verbal and graphic representation (sketch-maps) they supplied regarding their movement. The rest of the paper includes several sections; the next section presents the methodology for our experiment. Section 3 presents the results of the experiment and their analysis; and in the last sections we present a discussion and some concluding remarks.

[1] The hippocampus is a component in animals' brain that plays a major role in spatial navigation.

2. Methodology

In the following, we explain the method used in our experiments, both in terms of constructing the virtual environments and in terms of running the experiments themselves. First, we explain the process that led to constructing a virtual environment that is based only on morphological considerations and holds different levels of complication, and thus different amounts of information. This environment is compounded of volumes that represent buildings and their spatial distribution that represents the urban setting. In the following, we start by explaining our considerations in developing the rules that govern the construction of the building blocks and of the setting of the entire environment. Then, we will explain the experiments themselves.

2.1. The vocabulary i.e. the building blocks

The aim of this work was to study the effect of the morphology of the built environment on people's spatial cognition. Thus, we wanted to avoid (as much as possible) adding any additional type of information to our environments. Therefore, in order to represent buildings in our virtual environments we had to choose a general shape that can represent buildings on the one hand, but does not refer to any specific building, on the other. We considered several options and eventually decided to start with a cube as this volume is associated (at least in Western culture, where we conducted our experiments) with the form of a general building. To increase the variety of the buildings in our environment we used three mechanisms: (1) Change of scale, (2) Rotation, and (3) Change of morphological complication:

2.1.1. Change of scale

The change of scale varies between minimal and maximal sizes of the cubes. The minimal size has been defined as $10 * 10 * 10\ m^3$, while the maximal size has been defined as $100 * 100 * 100\ m^3$. These values represent the range of sizes between an average urban residential block and a public or retail center. The distribution of the cubes' sizes is based on two different functions, as we will explain in the section on the urban setting (see below).

2.1.2. Rotation

As the shapes in our environment are based on orthogonal angles (the cube), we wanted to avoid the creation of an orthogonal grid which can be associated with modern American cities. Thus, the orientation of each cube on the environment's plateau was rotated by a random degree between 0 and 90.

2.1.3. Change of morphological complication

The last mechanism was used to increase the complication of the cube without indicating any reference to a specific building. For that, we used the Grasshopper plugin on Rhinoceros©[2] to develop a script that converts the cube into more complex morphologies. This script was written by architect Nimrod Serok and it works as follows: at the first generation (i.e. Euclidian cube) a division ratio and direction (x, y, z) are randomly selected. Based on these selected parameters, the cube is divided into two volumes (see Fig. 1 stage 2). Each of the new volumes can be either eliminated or change its size. The elimination was based on a predefined probability that was applied to all the following iterations. The change of scale was based on a unique size distribution that we used for all the cubes in a specific environment setting: a normal distribution of sizes or an exponential one. In the next section, we elaborate on the difference between these distributions and the considerations for choosing each of them for a specific case. When the size of a volume is changed, the change is proportional (considering the different sizes of its different faces and edges) and the reference point to

[2] A commercial 3D CAD software.

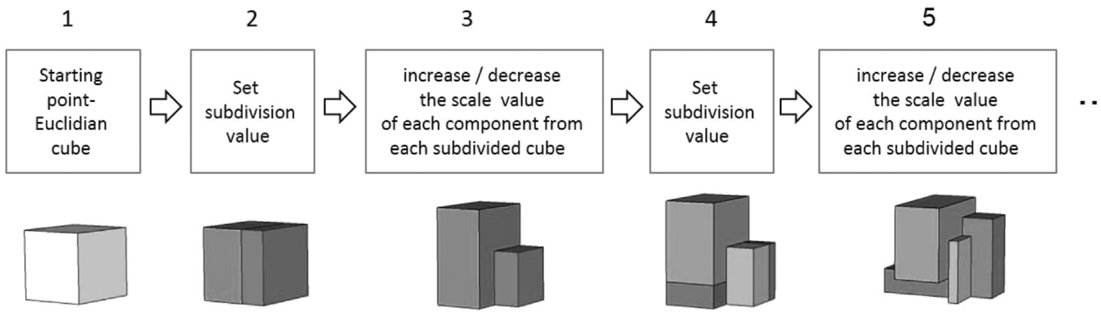

Fig. 1. The stages of the algorithm that increases the morphology's complexity.

the change is the nearest vertex to the center of gravity of the original volume (see Fig. 1 stage 3). At the next iteration, the same process is repeated, not on the original cube but rather on each of the new volumes (see Fig. 1 stage 4). Based on the above, we defined a function that represents the level of the morphological complication — f(Mc), where for f(Mc) = 0 the function describes the cube, for f(Mc) = 1 the function represents one subdivision of the cube, for F(Mc) = 2 the function represents 2 subdivisions of the cube and so forth (see Fig. 2). In the presented work we used the range of f(Mc) = 0 to F(Mc) = 6. As the resulted elements are no longer cubes, we refer to them from this step onwards as volumes.

2.2. The urban settings

To simulate an urban environment we used a 1000 $*$ 1000 m^2 plateau on which we placed 400 volumes that represent different buildings. These parameters create a density that is a typical average of real urban densities around the world. We wanted to examine two substantially different urban settings that represent qualitatively different situations in terms of information. The first situation represents a homogenous environment and the second represents a heterogeneous one. To be able to compare these two environments we kept the densities of their floor areas very similar: the homogeneous environment is represented by a density of 0.31 and the heterogeneous one is represented by a density of 0.36.

2.2.1. The homogeneous environment

In a homogeneous environment the level of information is very low. This is valid regardless of the number of elements in the environment. A good example for this can be found in a comparison between a forest and a desert. Even though the forest is full of trees and the desert is empty of trees (but full of other elements and long distance views/ cues), both environments are homogenous and give very little information to someone who is trying to navigate there. To simulate such an environment we have decided to normally distribute the sizes and the level of complication of the volumes in the environment. In a normal distribution, the majority of the elements in the set (about 68%) have values that are less than one standard deviation from the mean, and more than 95% of the elements in the set have values that are less than two standard deviations from the mean. This means that most of the elements in the set have similar and a rather small range of values, i.e. characteristics.

To create such an environment, we returned to the mechanisms that control the building blocks (described above) and used a normal distribution to control both the scale of sizes and the level of complication for these volumes. The result was a homogenous environment where most of the volumes had similar sizes and similar levels of morphological complication that were close to the mean level of complication (see Fig. 3). Note that such similarity does not indicate that the volumes themselves are alike. On the contrary, due to the algorithm we activated on the cubes, at f(Mc) = 3 the diversity of optional elements is rather high.

2.2.2. The heterogeneous environment

As opposed to the homogeneous environment, the heterogeneous environment provides a higher level of information. This can be associated with a medieval town where most of the buildings are very small and similar and most of the streets and public squares are narrow, with the exception of the high street, the church and its surrounding square. In such a place, it is easy to locate one's self in accordance with these dramatically unique elements. To create such an environment we decided to follow an exponential, heavy tailed distribution. Heavy tailed distributions are known to fit many complex systems and urban systems in particular (Batty, 2006; Benguigui and Blumenfeld-Lieberthal, 2007a, 2007b; Jiang, 2013b). These distributions describe a set, in which most of the elements have very small values and a small fraction of the elements have a considerably larger value than the mean of the entire set. A well-known description for such distribution is the 80–20 rule that states that 80% of the elements in the set are accountable to 20% of the measured values (i.e. money, in income distributions) while 20% of the elements in the set account for the remaining 80% of the measured values. Based on the above, following the exponential distribution resulted in an environment in which most of the volumes are small and very few are considerably large, and also, most of the volumes hold low levels of morphological complication while very few are represented by the highest level of morphological complication (see Fig. 3). Note, that the largest volumes are not necessarily the most complex ones and vice versa. In other words, the majority of the elements in the heterogeneous environment are similar to each other (as they share similar size and level of morphological complication) and few are significantly different.

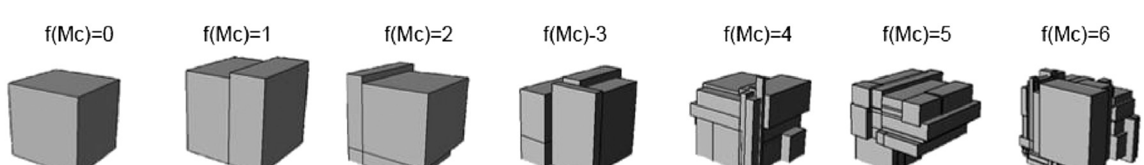

Fig. 2. Morphological examples for the subdivision of the cube at different f(Mc).

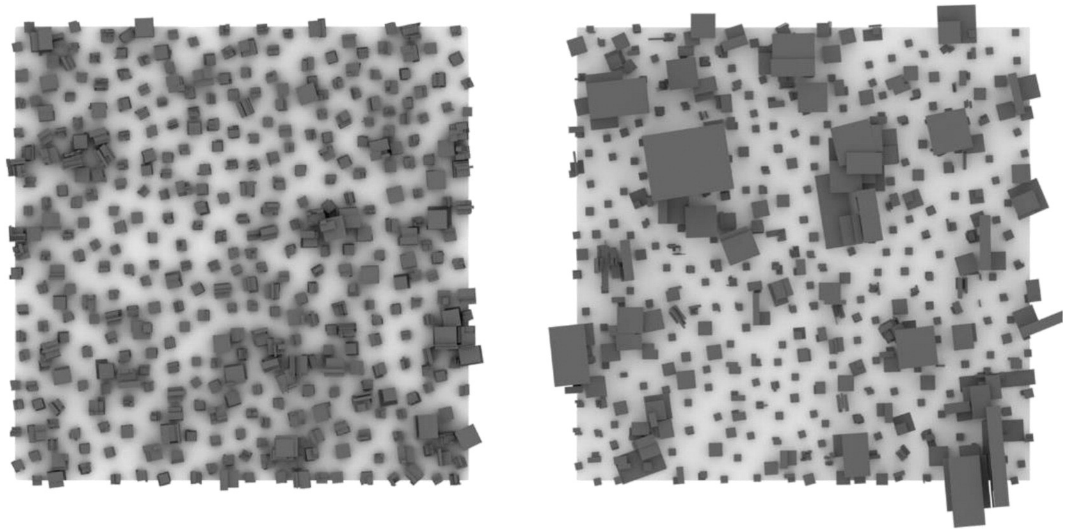

Fig. 3. The “Homogeneous city” (left) and the “Heterogeneous city” (right).

2.3. The experiments

As the purpose of our work was to examine the level of effect the morphological information has on the way people perceive the environment, we had to import our virtual environment into a platform that allows navigation in real time. For that, we used a couple of Presagis©[3] software tools: a virtual reality in real time generator called VegaPrime and a converting tool that is used to create or convert 3D models from a verity of alternative 3D modeling software, called Creator. The environment was played on 3 adjacent 46 inch Samsung LED screens as presented in Fig. 4.

We ran the experiment with 26 participants (males and females), all of them are undergraduate student in the David Azrieli School of Architecture at Tel Aviv University. The participants were asked to actively explore the simulated environments in both the Homogeneous and the Heterogeneous scenarios, during a period of 10 min for each scenario. By that, we aimed to explore their natural movement in the environment, based on Turner and Penn (2002) who defined natural movement as one that can be characterized by “we look around” and “we go from one vista to another”. They argue that in “natural movement, an agent does not even require the ability to recognize ‘object’ as distinct from ‘environment’: the agent merely has to recognize that there is an environment which may be explored in order to move (though not necessarily to navigate)”. During their exploration of the environments, we used a tracking algorithm that stores the x, y location of the user every 0.5 s. This algorithm was developed for this purpose by Synergy Integration Ltd. The output of the tracking algorithm was then used on a grasshopper script (written by architect Amir Levanon) which presents the track on a map of the environment. After the 10 min period each participant spent in each of the environments, we asked them to implement several tasks: the first task was to describe the environment they explored using a graphic representations (i.e. sketch maps). Then, we presented them with a map of the environment they explored and asked them to draw (from memory) the trajectory of their tour in it. Lastly, in order to explore the phenomenological aspects of the participants' experience in each environment (based on the Phenomenology of Perception of Merleau-Ponty's, 1962), we conducted an open, guided interview with the participant, where they were asked to verbally describe the environment they explored with emphasis on their feelings in terms of orientation and comfort. Fig. 5 presents the different phases we used to create the simulated environments.

[3] A provider of modeling, simulation, and embedded display graphics software.

3. Results and analysis

We divide the results into several sections based on the tasks the participants were asked to complete. First, we present results of the graphical representations of the different environments and the verbal explanations related to them (gained from the interview). Then, we present the trajectories the participants drew on the maps they were given, and compare them to their actual trajectories during the 10 min tour in the virtual environments.

3.1. The results of the graphical representations and the interviews

To present the results of this part of the work, we examined, for each participant, the graphical representation he or she provided together with the answers he or she gave during the following interview. Then, we defined several parameters that seemed to repeat in many of the participants' products. These parameters are:

- *Large open-space/Semi-squares*: this parameter indicates a verbal/graphical description of a geometrical void, defined by surrounding volumes.
- *Borders*: indicate a clear definition of boundaries that separate the environment from its external contexts.
- *Landmarks*: unique elements that were described as significantly different from their surroundings.
- *A detailed description of a unique element* (can refer to scale or form complication): indicates a specific description of a unique volume. This parameter was usually found in the graphical description and not in the interview.
- *Similarity between elements*: indicates a situation where the participant used the same language (graphical or verbal) to describe all the volumes in the environment. This applies in terms of scale as well as form complication.
- *Sense of orientation in the environment*: this parameter was defined based on the interviews.
- *Comfort*: this parameter indicates a general feeling of comfort, expressed in the interview.

The main results, gained from this part of the experiment concern two major aspects: the way the participants addressed the built volumes and the way they addressed the open spaces. As we analyzed the answers of only 26 participants, and as this analysis is based on a qualitative categorization of their products (interviews and sketch

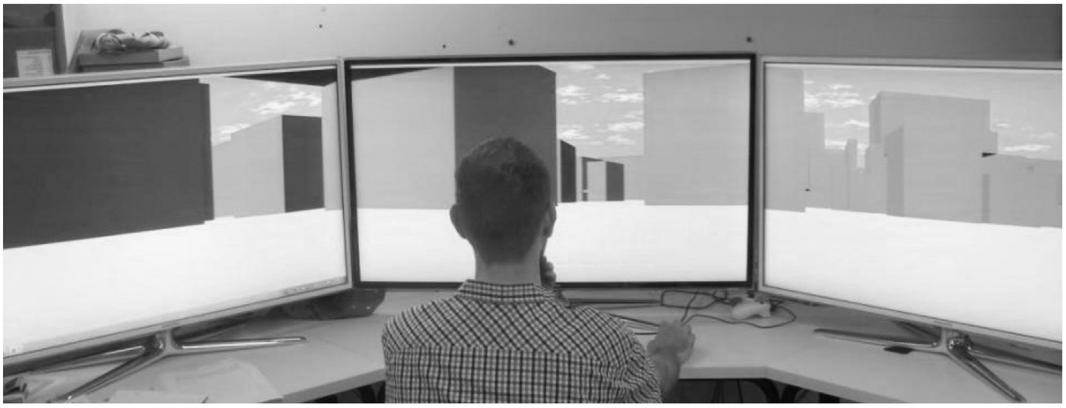

Fig. 4. The virtual environment display on the 46 in. screens.

maps) we present the result as percentages that indicate general trends and ignore statistical measurements. This is due to the fact that in addition to the number of the participants, any decision made at the qualitative level may have a major effect on the results and thus any accurate statistics cannot be validated.

In terms of the built volumes, the participants' descriptions refer to the general characteristics of the volumes as well as to unique elements which were conceived as landmarks. An analysis of the parameters, defined above, reveals that 73% of the participants mentioned the existence of landmarks in the heterogeneous environment while only 15% of the participants mentioned landmarks in the homogeneous environment (in terms of numbers these are 19 participants compare to 4). However, when examining the *detailed description of a unique element* (and not just the mentioning of landmarks) the differences between the two environments seem less significant. While 58% of the participants provided a detailed description of a unique element that differs from its surroundings in terms of form complication in the heterogeneous environment, 50% of the participants did the same in the homogeneous one. Yet, it seems that the difference in size had a greater effect on the participants' perception, as 65% of them provided a detailed description of a unique element in terms of size when referring to the heterogeneous environment, in comparison to only 42% who did the same in the homogeneous one. Despite the fact that most of the elements in the heterogeneous environment were more alike than the elements in the homogeneous one (see explanation in the section on the urban settings), it seems that the participants perceived the situation differently; while 85% of the participants exhibited similarity between elements when referring to the homogeneous environment, only 15% of the participants did the same for the heterogeneous one. Fig. 6 presents an example to such a graphical description. Note that in the description of the homogeneous environment most volumes are represented as extremely similar in size and morphology while in the heterogeneous environment there are notable differences between the volumes. These differences are clearer in terms of size but also appear in terms of morphology.

In terms of the open spaces, it seems that the participants exhibited a clear distinction between the two environments. This distinction is expressed in several of the examined parameters; the first parameter we examined in this context is the existence of large open spaces or semi-squares. While only 50% of the participants (i.e. 13 participants) referred to this parameter in the homogenous environment, 81% of them (i.e. 22 participants) presented large open spaces in their descriptions of the heterogeneous environment. Fig. 7 is an example for a graphical description of one of the participants. It can be seen that while the homogeneous environment is described as volumes that are equally distributed in space, in the heterogeneous environment there is a clear and defined open space that can be referred to as an urban square. It is important to remember that both environments were created by an algorithm and the spatial distribution of the volumes was random. In fact, no urban square was actually planned or existed in either one of the environments, as can be seen in Fig. 3.

Another example for the description of open spaces can be seen in Fig. 8, where the participant not only described one urban square in the heterogeneous environment but drew several of them. The text he wrote near the graphical description says: "top view; there was a feeling that there were more squares between the buildings. The squares are marked by circles".

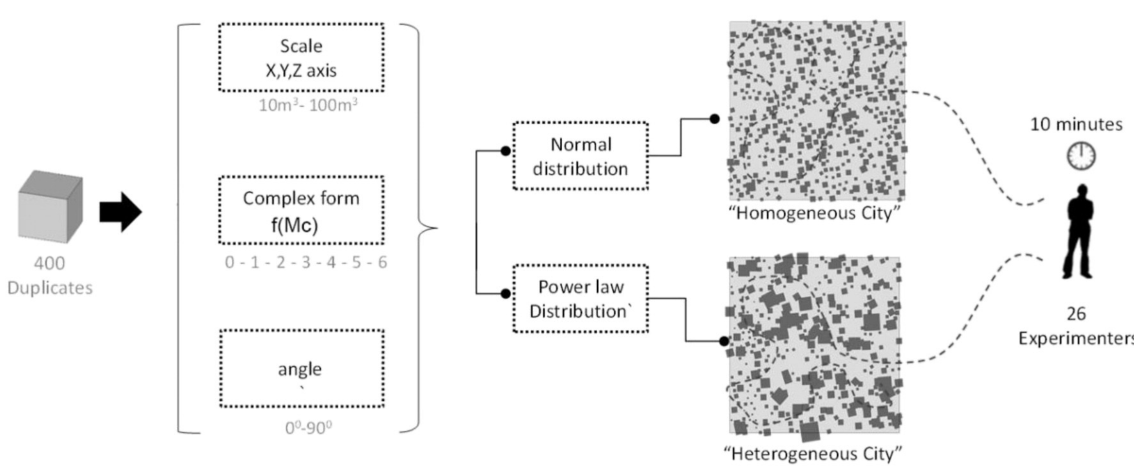

Fig. 5. The stages of the experiment's methodology.

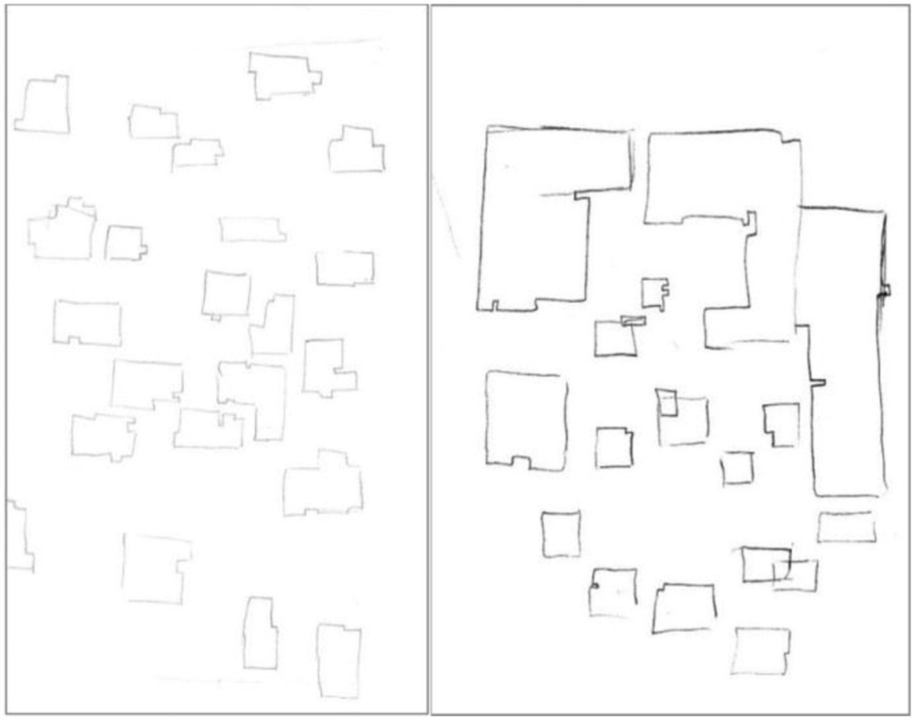

Fig. 6. A map of the homogeneous environment (left) and the heterogeneous one (right), drawn by one of the participants. Note the similar representation of the element in the homogeneous environment in comparison to the different elements on the heterogeneous one.

The same situation applies to the issue of borders — despite the fact that in both of the environments there was no real definition of borders and the volumes were randomly distributed regardless of their distance from the edges of the environments, some of the participants described borders in their descriptions. Here also, there is a notable difference between the homogeneous environment and the heterogeneous one. While 35% of the participants described borders in the heterogeneous environment, only 19% of them did the same in the homogenous one.

During the interviews, the participants were asked about the way they felt in both environments. More than 50% of them (14 participants) mentioned that they had a sense of orientation in the heterogeneous environment; for example: "*Although it was a geometrical environment, there was an orientation feeling*" or "*You can see the skyline form every standing point*". However, only 8% (2 participants) felt the same in the homogeneous environment, while others expressed the opposite feeling, for example: "*You cannot know where you go*" or "*There are only alleys with no streets*; *there is nothing to follow*".

In terms of their general feeling in the different environments, almost 80% of the participants (20 out of 26) referred to a comfort feeling they had in the heterogeneous environment (e.g. "*I felt protected*" or "*A safe feeling, like I am not alone*, *someone is always looking at you*". On the other hand, less than 30% mentioned such a feeling in the homogenous environment, and others mentioned the contrary feeling, for example: "*There is no safety feeling. It is boring as well*" or "*The environment is not interesting because it is anonymous*".

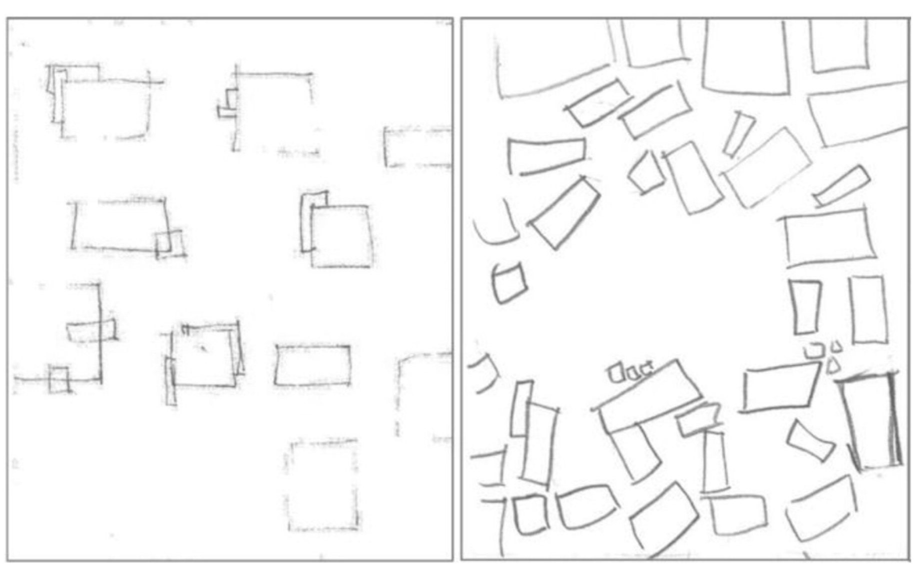

Fig. 7. A map of the homogeneous environment (left) and the heterogeneous one (right), drawn by one of the participants.

Fig. 8. A map of the heterogeneous environment drawn by one of the participants. The circles represent urban squares.

3.2. The trajectories in the different environments

In this section we present the trajectories the participants followed in the two environments and compare them to the way they perceived their tour. We start with the actual movement of the participants in the two environments and compare them. For that, we used the output of the tracking algorithm and a grasshopper script which presents the trajectories on a map of the environment (as described in the methodology section). We used Adobe Photoshop© to create a superposition of the trajectories of all the participants in order to find the dominant areas in the environments. Fig. 9 presents the trajectories of all the 26 participants on the map of the homogeneous (right) and heterogeneous (left) environments. The black lines represent the trajectories of the participants and the width of the lines represents the attractiveness of the route, meaning the number of different participants who moved there. The starting point of all the participants was at the bottom-left side of the maps in both of the environments. It can be seen that there is a qualitative difference between the ways the participant moved in the different environments; the movement in the homogeneous environment seems to follow a lengthwise and crosswise pattern, where the trajectories are rather continuous in their directions but do not depend on the orientation of built volumes. The movement of the participants in the homogeneous environment covered most of the area and the boundaries of the environment have been reached. On the other hand, the movement in the heterogeneous environment is more object-oriented, meaning that it depends on the location of the largest volumes. As opposed to the homogeneous environment, here, the trajectories surround the largest objects, resulting in loops that enclose them. In terms of area coverage, it can be seen that the movement of most of the participants is centralized and not all the boundaries of the environment have been reached.

Next, we discuss the way the participants perceived their movement in the environments. Fig. 10 presents the superposition of all the trajectories the participants drew when asked to reconstruct their journey in the homogeneous environment (left) and the heterogeneous one (right). Here also, the black lines represent the trajectories of the participants and the width of the lines represents the attractiveness of the route. At first glaze, a comparison between the two environments reveals similarity (which deviates from the actual trajectories the participants did as seen in Fig. 9). However, a closer inspection shows that in fact, there are substantial differences between them. These are the coverage of area, the orientation of the movement, and the radii of the loops. It seems that in the homogeneous environment, the participants felt they covered a much smaller part of the environment than they actually did. This can be associated with the fact that most of the participants did not indicate the existence of borders in the homogeneous environment. To their perception, the entire area was pretty much "more of the same" and even though they reached the boundaries of the environments they didn't realized it. Going back to the image we gave at the beginning of the paper, this can be understood by means of someone walking in a forest. Even if the edges of the forest are very close to him, the homogenous distribution of trees prevents him from getting the full picture of the area. In terms of orientation of movement — there is a small similarity between the actual movement and the perception of the participants in terms of the horizontal axis (on the map). Yet, the vertical axis which was very dominant in the participants' behavior does not appear in the way they describe their movement. Instead, many small loops appear in their descriptions. In the heterogeneous environment, on the other hand, there is good agreement between the actual trajectories of the participants and the way they perceived it. It can be seen, that the area that was covered in the real movement matches the area the participants drew. The orientation of the movement as well as the size of the loops and their location (around the largest volumes) fit the actual trajectories as well. This implies that the heterogeneous environment was perceived in a rather accurate way by the participants. In fact, this finding is supported by the way the participants expressed themselves in the interviews, regarding the sense of orientation they had in each environment.

4. Discussion

The key objective of our work was to explore the influence of different informative levels of the built morphology, presented by different environments, on people's spatial perception. To explore this, we conducted an experiment in a 3D virtual environment. For that, we developed two theoretical urban settings; the first represents a homogeneous environment and the other represents a heterogeneous one. To create these environments, we used an algorithm that distributes the sizes and the levels of morphological complication of the built elements in these environments, based on two size distributions: a normal distribution that is associated with the homogeneous environment and an exponential, heavy tailed distribution that yielded the heterogeneous one. Based on Haken and Portugali (2003) we assume that the homogeneous environment supplies a low informative level in terms of its morphology. This is because the normal distribution results in an environment where most of the built volumes are similar in their sizes and in their level of morphological complication; however, there is a large variety of different volumes as the mean level of complication is around $f(Mc) = 3$. This corresponds to an urban area where all the houses are different from one another and thus cannot be grouped into similar classes. The informative level of such environment is therefore poor in terms of built morphology information (see elaboration in Haken and Portugali, 2003). On the other hand, the heterogeneous environment we created was based on the exponential distribution. Thus, it was compounded of many built volumes which were similar, small, and with a low level of morphological complication, and of very few large and highly complex ones. Such an environment can be compared to an urban area with many similar houses and few landmarks that increase the informative level of the morphology which the street provides.

As we wanted to use sketch maps, which are graphical representations, as a means to examine spatial perception, we wanted to guarantee a minimal level of graphic skills and spatial perception, thus we ran the experiment with 26 participants; all of them are architectural students. Each participant was asked to explore each of the environments for a period of 10 min, after which they were asked to describe their experience in the environment graphically and verbally. The analysis of our results suggests that there is an apparent difference between the way the participants moved in the homogeneous environment and the heterogeneous one. In addition, we found a remarkable difference between the ways the participants perceived the two environments. In terms of movement (see Fig. 9), the spatial exploration of the homogeneous environment covered most of the environment in a lengthwise and crosswise pattern. This pattern is based on continuous trajectories that do not follow the shape or orientation of the built volumes in this environment. In the heterogeneous environment on the other hands, the movement of the participants followed the location and orientation

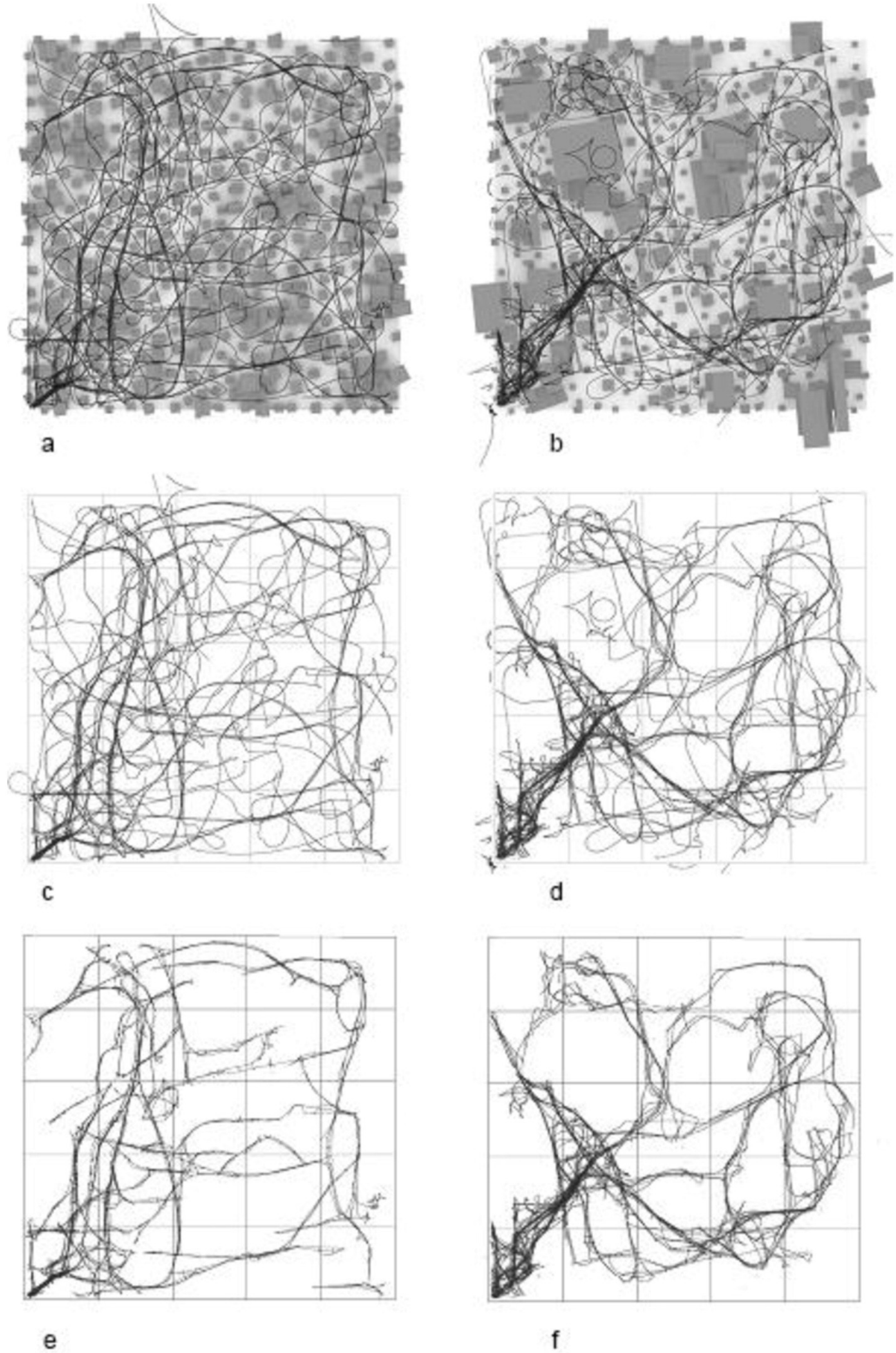

Fig. 9. The trajectories of the participants in the homogeneous environment (left) and the heterogeneous one (right). (a) and (b) present the trajectories on the maps of the environments while (c) and (d) separate the trajectories from the environments. In (e) and (d) we show the trajectories that were used more than once.

of the largest volumes, and the trajectories surrounded these volumes forming a pattern of large loops. In terms of area coverage, the nature of the movement was also different from the homogeneous environment. In the heterogeneous environment, most of the participants centralized around the large built volumes, and thus, did not cover the entire environment. In terms of spatial perception of the environments, we can divide our results into two major aspects; the way the participants perceived their movement and the way they perceived the environments. A comparison of the maps the participant drew after exploring each environment (Fig. 10) shows that there is a qualitative difference between the actual movement of the participants in the homogeneous environment and their graphical description of this movement. The sketch maps displayed many small loops that have nothing to do with the actual movement of the participants (see Fig. 9c in comparison to Fig. 10c). An explanation to this perception can be found in the fact that both animals and humans tend to move in circuitous paths when faced an environment with no unique references/landmarks, which is also valid to movements in dark environments (Souman et al., 2009; Yaski et al., 2009). As the homogeneous environment does not provide any external reference or landmark, it is logical to assume that when the participant tried to reconstruct their trajectories from their memory, they relied on their instinctive tendency to move in loops. On the other hand, there is good qualitative correlation between the trajectories of the participants in the

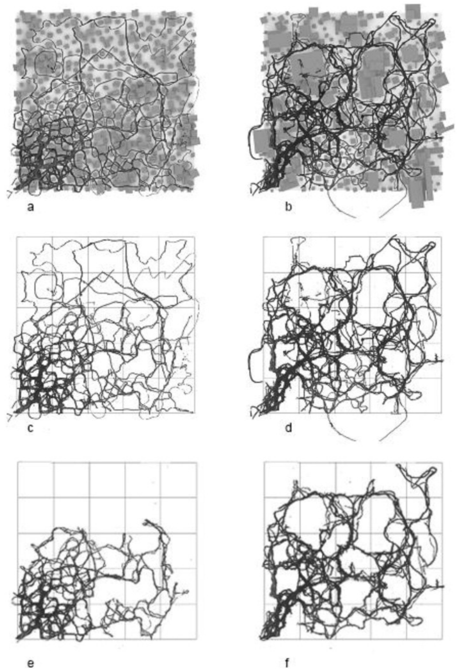

Fig. 10. The trajectories of the participants drew of the homogeneous environment (left) and of the heterogeneous one (right). (a) and (b) present the trajectories on the maps of the environments while (c) and (d) separate the trajectories from the environments. In (e) and (f) we show the trajectories that were drawn by more than one participant.

heterogeneous environment and the way they perceived their movement. It can be seen from Fig. 9b that the participants moved around the largest volumes which were located approximately in the center of the environment. These volumes can be treated as landmarks that stood out in the field of small simple volumes. In terms of information we claim that these results support Haken and Portugali (2003) who linked the informative level the environment provides to the spatial perception of people who explore it. Our results also support Jiang (2013a) who showed that many rank size distributions of cities' artifacts fit heavy tailed distributions where the head comprises of the minority of the most vital, large, or important elements and the tails contains the majority of the non-important artifacts (also in Jiang, 2013b). To his claim, the elements in the head of the distribution are the most memorable and thus have significant role in the way we perceive the environment.

5. Conclusions

To our knowledge, this work provides for the first time empirical information to support the above arguments. This can be easily seen in both the maps of the trajectories the participants drew and in their graphical and verbal descriptions of the environments. When examining the graphical and verbal descriptions of the environments, it can be seen that the products of the participants also demonstrated significant differences between the ways they perceived the homogeneous environment in comparison to the heterogeneous one. The most common characteristics among the participants regarding the homogeneous environment was the similarity between the objects (85% of the participants) while the heterogeneous environment was described by other urban characteristics that can be associated with Lynch's images of the city. For example, 73% of the participants mentioned landmarks and 65% of them described at least one of the large volumes in particular, 81% of the participants described urban squares (that can be interpreted as Lynch's *nodes*), and half of the participants mentioned that they felt a sense of orientation in the heterogeneous environment (in comparison to 8% that felt the same regarding the homogenous one). This sense of orientation can be understood as Lynch's *imageability*.

To summarize, we showed that, in terms of morphology, heterogeneous environments which are characterized by a heavy tailed distribution of their built elements provide higher informative level and thus present better *imageability* than homogeneous environments that are characterized by normal distributions of their built elements.

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