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Abstract

From physics to social sciences, information today is seen as a fundamental aspect of reality. However, one form of information still seems underestimated, perhaps precisely because it is so present. We do not fully understand how cities materialize information, and how our minds deal with this environmental information to learn about the world, make decisions, and participate in the complex system of social interactions. This paper addresses three issues that need to be addressed if we are to understand the role of environmental information: (1) the physical problem: how can we preserve information in the built environment? (2) the semantic problem: how can physical form convey meaning? (3) The pragmatic problem: How do we use environmental information in our daily lives? Looking for answers, we introduced a three-layered model of information in cities, namely: environmental information in physical space, environmental information in semantic space and practical information exchanged by agents. We propose ways to estimate information in these different layers and apply these measures in simulated scenarios and in emblematic cities in different regions of the world. Our results suggest that spatial structures and land use patterns encode information and that aspects of physical and semantic information affect coordination in interaction systems.

Keywords: Information, Cities, Interaction, Environmental information, Entropy

1 Introduction: complex systems in relation

Look out of your window. You will see differences in the shapes and sizes of buildings, some perhaps taller and more concentrated in certain parts of the city. You will find that these buildings are connected to the streets and that they are probably also different from each other. Even if you have never been to this city or area before, you can walk through it and find someone or something you need on a busy street. You can situate yourself and find your way. You never thought about it, but this is a condition for being where you are right now. In fact, you live within a pattern: the interaction of recognizable relationships and variations between spaces, a mix between hierarchy and contingency, a balance between order and surprise. Because these patterns involve tangible spaces, people's activities, and their ability to do things together, this is both material, cognitive, and social interaction —all at once. You live the interaction of minds, cities, and societies. Although each of these systems is complex in itself, the interesting thing is that they eventually relate. Working together, minds, cities, and societies somehow "merge" into one immensely interactive system.

This article deals with how we use information in our environment to act collectively on this hybrid system. It deals with the mutual construction of information, both in the environment and in our perception and in the 'weaving of social life'. We will see the city as layers of environmental information essential for human interaction and cooperation. To this end, it explores various theories such as information, cognition, and social systems. For example, we learn from cognitive science about how humans relate to information in their environment. Various approaches claim that our minds not only decode environmental information but also extend to the environment (Varela et. al., 1991; Lakoff and Johnson, 1999). We want to explore possibilities related to this idea: how information is preserved in the built environment and how this information supports our interactions.

This means exploring the transition from information to interaction. This transition seems to be at the heart of a big problem: How do we connect our actions to create a society? How can individual actions develop into a coherent system of interactions? How do we coordinate the individual decisions of huge numbers of people? Let us argue here that the way we organize ourselves in society depends crucially on how we deal with information in our environment.

How does this happen? One thing that minds, cities, and societies have in common is information. They depend on it. Minds process information. Societies exchange information to exist. The built environment has structures that can contain information. These systems process, share and preserve information. Was information the bridge between them?

Understanding the connections between minds, cities, and societies requires several methodological steps. First, let's introduce a conceptual model of 'city as information' in three layers. Then we will propose information measures for these layers, and apply them to selected urban cases from different regions of the world, and to simulated scenarios.

2 From information to interaction

The seminal book by Shannon and Weaver (1949) stimulated most discussions about information. Interestingly, Weaver offers a way to understand the relationship between our minds, environment, and interaction by asking three questions: "(A) How accurately can symbols of communication be transmitted? (the technical problem). (B) How accurately do symbols convey the desired meaning? (the semantic problem). (C) Does the meaning received affect the conduct as desired? (the problem of effectiveness)". The relationship between cognition, environment, and interaction involves analogous questions:

1. How do we encode and decode information from the environment? (the physical problem)

2. How can physical space convey meaning? (the semantic problem)

3. How does environmental information affect our actions? (the pragmatic problem)

We will see that information is somehow embedded in tangible spatialities that humans create as their environment. In turn, semantic information is created as meaningful content in buildings and places associated with certain activities. We seem to recognize places as configurations related to our actions and a shared idea of what they are. Finally, the pragmatic problem involves how we use environmental information to guide our actions and create interactions. We propose to deal with these forms of information in three interactive and overlapping layers (Figure 1).

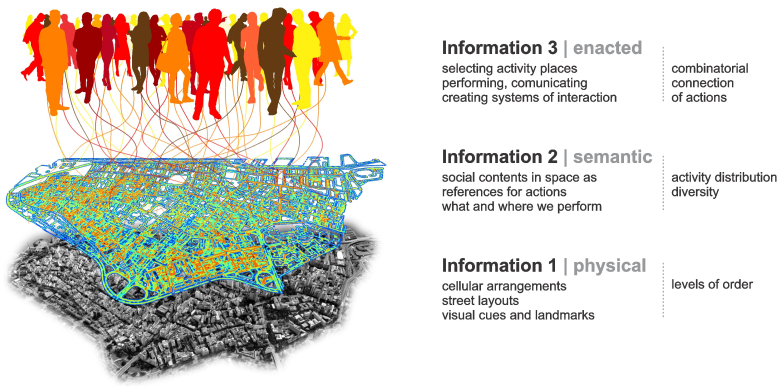

Fig. 1: Environmental information (1) physical space and (2) semantic space and staged information (3): substantive components and measurable properties. Source: Authors.

Classical theories deal with these forms of information to different extents. For example, Lynch's "city image" (1960) operates primarily at information level 1, as it deals with physical paths and clues related to cognition and navigation. Hillier's (1996) spatial syntax apprehends accessibility patterns in street networks related to cognition, movement, and encounter. The synergistic inter-representation networks of Haken and Portugali (2015) unite Shannon and semantic information as the basis for actions in the city, but without the systemic aspect of social interaction.

Our theoretical model places the physical layer at the bottom as the elementary and fundamental layer of information related to our cognition and navigation. The layer includes the arrangement of elements such as buildings and streets and the relationships between them. In addition, it is a very stable form of information that changes slowly. In turn, the semantic layer has to do with how buildings and places support our actions. Its stability depends on how long actions are performed in these places and how long their meanings are retained in people's memories, so it changes more easily.

Environmental information 1 and 2 are inseparable, but not necessarily intrinsic to each other. Although a building is designed to support a certain activity, it can be used for different activities over time, sometimes without the need for physical adaptation (for example, a house becomes a store or an office). Thus, physical information tends to remain, while semantic information depends on the ongoing actions and memories provided by the building. Finally, practical information layer 3 includes the effects that places and their meanings have on agents, bringing possibilities of action (Kuppers, 2013). Actions include speech, body gestures, and the production of signs and objects that carry meaning, and are therefore understandable by other agents, triggering interactions (Habermas, 1984). Information 3 is created in the transition between cognition, environment, and interaction. It involves environmental information whenever we use the environment around us to make individual decisions, act and communicate.

Now let's look at what each layer individually is and how they interact like a single system, uniting minds, cities, and societies (Figure 2). The environment we humans create is made up of tangible and non-tangible structures, an interaction of physical spaces (environmental information 1) and configurations of meanings in spaces and places (environmental information 2). People ('agents') encode information and decode environmental information and relate to it via perception and cognition. In turn, cognition is situated because it extends to action and arises from interactions between agents and their environment. Cognition emerges from interactions as distributed processes in collective operations between agents (Hutchins, 1995). As we shall see, this extension of cognition in the environment and the way agents coordinate their actions is the definition of "enation" (Varela et. al., 1991), or what we call practical information 3. Information 3 encompasses perception, cognition and situated interactions and is deeply related to their environment.

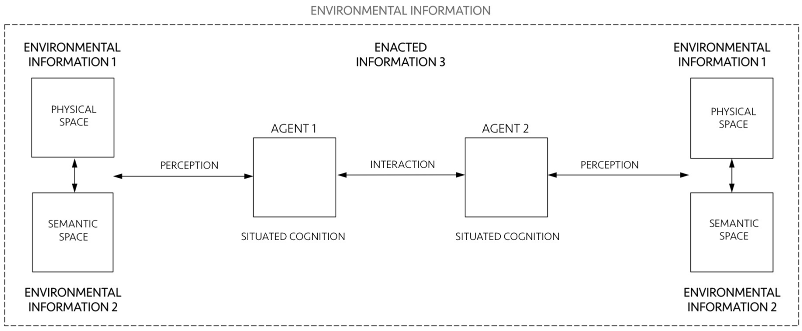

Fig. 2: Schematic diagram of a general information-interaction system. Source: Authors.

Of course, all of these items and relationships have been heavily researched and need detailed definitions. We will approach them following the conceptual architecture of the three layers.

3 Environmental information 1: the physical space

Since Shannon's (1948) pioneering work on the mathematical theory of communication, the notion of information took on other disciplines in the 1950s and 1960s. Shannon came to a clear description of information through a probabilistic definition of entropy, also explored by physicist Boltzmann (2015 [1873]) before him. For both, entropy is a measure of the uncertainty of a system. The greater the number of potentially transmitted messages (Shannon, 1948) or the number of distinct microscopic states of a thermodynamic system (Boltzmann, 2015 [1873]), the greater the corresponding entropy. Since Boltzmann, entropy has been associated with the disorder (Prigogine and Stengers, 1984). Higher entropy physical arrangements are characterized by higher levels of randomness, unpredictability or uncertainty. In turn, predictability levels may be associated with the order. Ordered structures contain correlations such as similarities, consistencies, and associations that may be seen as the "substance" of information, as pieces of "coherence above and beyond grouping and dispersing entities" (Bates, 2006, p.1034).

The fact that information can be encoded in physical structures is interesting. Information lasts longer when preserved in tangible entities (Hidalgo, 2015). If physical spaces materialize information, we have a way of expressing information continuously as long as these spatialities exist. We can encode information in the built environment and decode it while we live in it. This would open extraordinary cognitive possibilities to guide our actions.

But how can we encode information in the built environment? At this point, there seems to be no definitive answer to this question. Research in the field of spatial information seems to focus mainly on how we decode environmental information - for example, the role of perception and visual elements in navigation and spatial decision making (Garlandini and Fabrikant, 2009). Empirical work in neuroscience confirms that neural algorithms 'integrate' information about place, distance, and direction, forming topographically oriented and neural maps of the spatial environment. "Grid cells" in the brain are activated whenever our position coincides with vertices of a regular hexagonal grid spanning the surface of the environment, being critical to our goals and navigation plans (Hafting et al. 2005).

One possibility under increasing attention in this field is that levels of regularity, alignment, and predictability in spatial arrangements are cognitively useful for anchoring our internal navigation system (see Ekstrom et. al, 2018). We can capture levels of physical information by recognizing the regularity of spatial event frequencies in the environment. If this is the case, the greater the variation of elements in the environment, the lower the regularities that would allow us to understand more quickly and make inferences about the space around us. But which spatial arrangements contain more physical information?

We suggest that one way people create information 1 is by generating levels of order in the deepest elements of the built form: the aggregations of buildings shaping urban space. Imagine the projection of buildings in a two-dimensional space in the form of a grid. Buildings take the form of cells and occupy positions in this grid, making arrangements as in Figure 3. These arrangements display different levels of order, apparent in the frequency of distances between cells. An extreme case is an orthogonal arrangement (Figure 3, case 1). Perfectly regular arrangements like this are rare situations in the set of possible arrangements - like drops of order in a sea of disordered states. In most states, the distribution of cells tends to contain a few internal correlations, as in the second case.

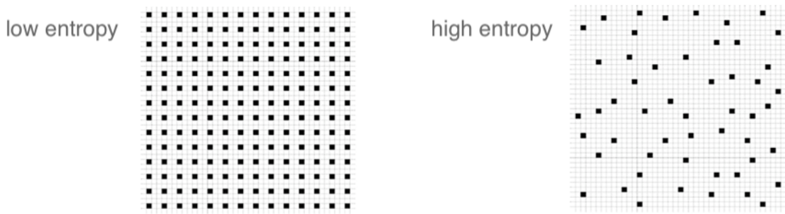

Fig. 3: Information in physical space: arrangements with different levels of entropy. Source: Authors.

We propose to analyze the predictability levels in physical arrangements using statistical concepts. An information measure 1 should be able to grasp regularities and variations in actual configurations and different urban situations. For this purpose, we suggest using Shannon's entropy (1948). As we have seen, high entropy corresponds to high levels of randomness or unpredictability. In contrast, the presence of regularities and patterns in urban structures corresponds to the lowest entropy. Hypothetically, cities with orderly structures would help agents understand their environment by allowing them to make predictions about areas beyond their field of visibility. People can make inferences, memorize layouts, and navigate more easily from one place to another - say, by grasping the pattern of blocks and intersections of local streets and inferring the structure of the surrounding blocks.

The measure of spatial entropy can be explored to characterize urban areas and cities from different regions of the world. This is what we did for emblematic empirical cases (figure 4). We are aware that some selected cases offer no evidence to validate a model. However, these empirical analyses are intended to illustrate the use of measurements, showing their utility in capturing levels of order and information in spatial arrangements. The measure of entropy should be tested for subtle variations in real urban settings.

We sampled 9,000,000m2 of geographic areas from public map repositories such as Google Maps, scaled to 10002 pixels in monochrome and converted to an array of binary values for built-up or free cells in two-dimensional space. We know that this is a reduction of real complexities, but the approach must be able to describe the urban form minimally and sufficiently - hence its reduction to cellular aggregations.

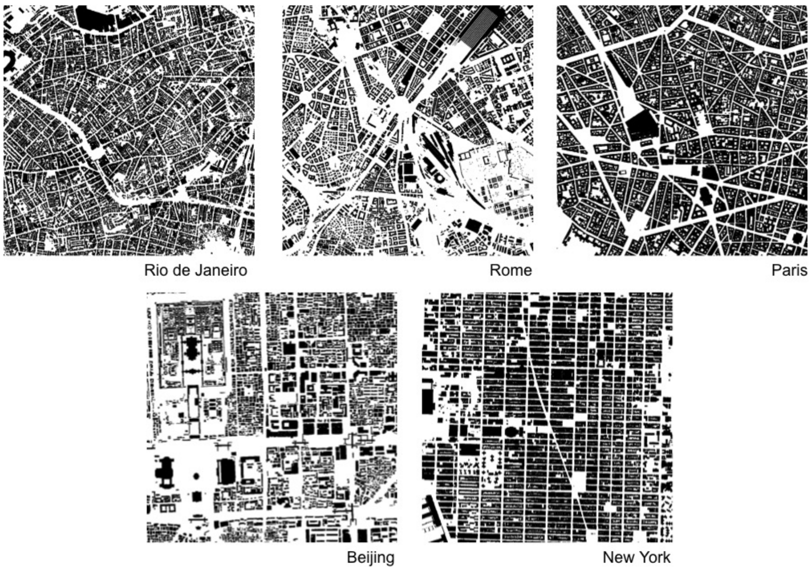

Fig. 4: Space distributions in real cities (9, 000, 000 m2, 1000 × 1000 cells) taken from Google Maps. These sections will be used to calculate Shannon entropy and to estimate the degree of disorder in cell arrangements. Source: Authors.

The analysis estimates the probabilities of distinct cell configurations and counts their frequencies in the actual structures (figure 5). For example, there are 512 different configurations for blocks with nine cells. Rio de Janeiro (Figure 5, left) shows a wide range of configurations of type (a). In turn, type (b) configurations are very common in Manhattan (figure 5, right). High repetition of the same settings approximates the entropy measure to 0, i.e. high levels of predictability. Already a low frequency of arrangements, with great variation and unpredictability means entropy levels close to 1.

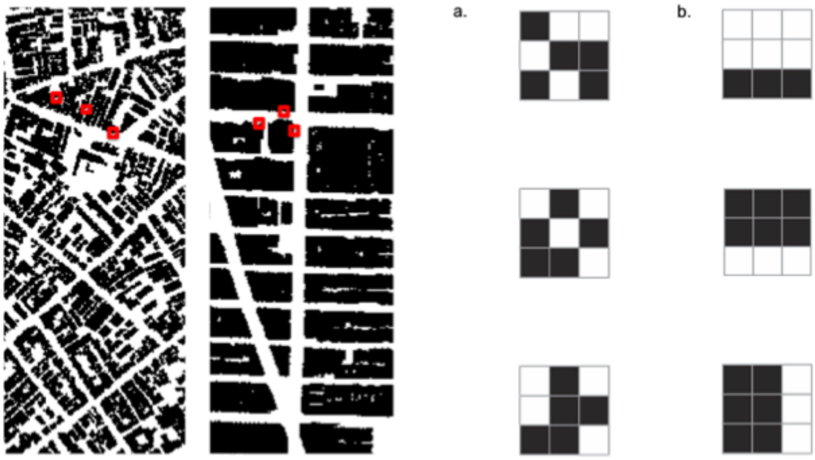

Fig. 5: Information on cell arrangements. Examples of nine cell blocks are shown in red for areas in Rio and Manhattan and amplified on the right. Rio shows a wide variation of type (a) configurations indicating many irregular formations, low predictability, and high entropy. Type (b) configurations are frequent in Manhattan, containing more regular training, high predictability and low entropy. Source: Authors.

Results for estimating entropy in areas of the five selected cities are shown in Figure 6 (Netto et al, 2018; 2019). The selected north area in Rio de Janeiro shows the highest level of disorder among the cities.

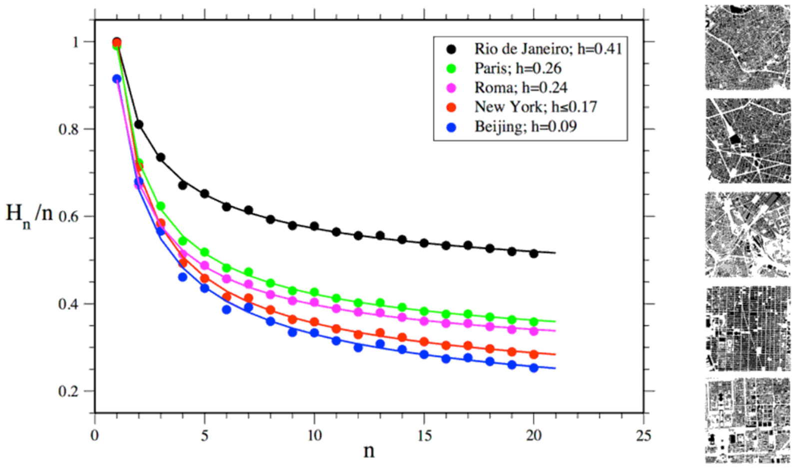

Fig. 6: Environmental information 1: Estimated entropy values for areas in five selected cities. Source: Authors.

It is interesting to note how physical information can be grasped even at small scales and that the disorder decreases as the size of the analyzed cell blocks increases, and as larger scales of order and correlation begin to matter. Levels of regularity in the physical space seem useful informational characteristics (cf. Haken and PortugalI, 2015). However, there may be a limit to the nature of the information that physical space can encode. What other aspects of the environment can preserve information?

4 Environmental information 2: the semantic space

The built environment can gain more information potential when its components assume social content and associations with people's actions. However, what is this informational potential? We can think of the difference between environmental information 1 and 2 as the difference between a black and white image and a color image. Compared to shades of gray, the colors are more diverse and contrasting. New possibilities emerge as each color meets its own palette of shades, leading to a huge increase in the combinational possibilities of colors and shades (Figure 7).

Fig. 7: Colors find their own palette of shades, becoming more diverse and contrasting in the shift from gray to color scales, leading to a huge increase in combinatorial possibilities. Photo: Vincent Laforet. Source: Personal collection of the authors.

Many studies on cognitive science and spatial information have affirmed associations between physical characteristics and semantic content in cities. Certain cognitive processes trigger associations with elements of the environment through the incorporation of socially acquired information (Taylor et.al., 2011). Information is classified into categories shared by people (Rosch, 1978). The likelihood of a building or place evoking a shared mental representation is reinforced by its appearance and visual identity, along with its visibility and location in the environment and the social information associated with the activities performed there (Golledge, 1992).

But how does semantic environmental information matter to our actions? Semantic associations with places increase the power of the environment to inform us (Taylor et. al., 2011; McNamara et. al., 1992). For example, we remember a restaurant more easily if we know that it is located near certain or another restaurant. Locational patterns like this work cognitively: activities in the same sector will often be located close to each other, competing or establishing complementarities, attracting more attention than if they were scattered and isolated.

Semantic similarity has already been proposed as a measure (Mülligann et al., 2011). We argue that another key point would be to measure the diversity of social content in buildings and places. We propose to deal with these shared meanings through semantic maps (Tversky, 1993). Semantic maps can represent any form of social content in urban space, including public space, such as a corner with street vendors, for example. Maps may not capture individual interpretations and memories of places, but they can capture their shared meanings.

These meanings are part of our knowledge of a city and its social world and support our understanding of the role of places in supporting our actions and interactions. Like any kind of social and environmental knowledge, it must be heuristically constructed from everyday situations. For simplicity, we chose classic categories in urban studies: land uses ranging from public squares to residential buildings in our analysis of two urban areas (Figure 8, left).

Fig. 8: Semantic maps: actual distribution (above left), as raised by Maraschin (2014), and fictional distribution (below left) of land uses in central Porto Alegre, Brazil. The values shown on the right (from blue to red) show levels of diversity between land use cells. Source: Authors.

Semantic information can be measured as levels of diversity found in land use distributions, a potentially attractive form of information for agents by analyzing local adjacencies between neighboring buildings or cells. We have to do this using a different procedure than we used to analyze information 1. We define a block of cells corresponding to a square. Within this square, we measure the distribution of land uses by the frequency of different uses. For example, in both cases in Figure 8, there are 8 types of land use. Then we estimate the information value for each area. The graphical analysis identifies high diversity arrangements in the maps, corresponding to the interfaces between land uses. The actual distribution is more diverse than the fictional one, suggesting that its cells encode more semantic information. These examples show the utility of the method for capturing information levels 2 in social content distributions in cities.

5 Information 3: enacted

Finally, we come to the problem of how people use environmental information 1 and 2 to act and interact. We call this ‘enacted information’ or information 3. This information exchanged by people from what they decode from the environment has been treated as ‘enaction’ in cognitive studies, as in Varela et al (1991). The enation is embodied in the sense that our cognition depends on the experience of bodies with sensorimotor capabilities situated in a broader biological, psychological, and cultural context.

At this point, we come to a fundamental problem in enactive approaches: *how does coordination arise between people?* The emission and reception of signals in language give rise to modulation and coordination between our actions. There is effective communication only if interactions result in this coordination (Stewart et al., 2010). At this point comes the role of the built environment and environmental information. Buildings and places mediate our interactions. The semantic layer of environmental information offers the enactive layer a means of establishing commonalities, a fine-grained reference system so that we can convey meanings in our communication, and to connect our actions. Places become us among our actions.

These connections progressively lead to true networks of interactions between places and people and what they do together. A physically and semantically structured space becomes a framework, a tangible form of organization for interactions.

Think of a place where you go in your daily life - say, on a busy street near your work. You do not go to this place arbitrarily or randomly. The physical and semantic environment ‘informed’ you (or informed the browser on your smartphone) that this place exists, and that it was a possibility for your action, a way to participate in this situation. The physical and semantic environment plays an active role in how you and others can act together, coordinating your actions.

In addition, this situation can be extrapolated to others. What happens there tends to have cascading effects, with actions and their outcomes connecting to other actions and places, merging into a huge web of interactions that unfolds on ever larger scales across different media and what structure the world around you, including your city and eventually other cities and regions of your country and the world. Environmental information becomes an elementary means of social organization - or a means of reducing entropy. This idea is consistent with enactive approaches: people rely on environmental information to cooperate.

But there are more roles for the environment in our interactions. Imagine now a problem we rarely think about: *How do we choose the people or activities we want to interact with?* Given the huge number of possibilities for interactions in a city, how can the built environment inform us and help us select places and make interactions?

One of the things to know here is whether different patterns, such as physical accessibility (information 1) or the distribution of activities in space (information 2) affect our choices and the combination of our actions. For example, different levels of activity diversity may have different effects on people's actions. We propose to evaluate the possibilities of action combinations in different spatial scenarios, such as those in Figure 9.

Fig. 9: Does the semantic arrangement influence the coordination of our actions? Agents converge on a fictitious, almost random distribution (left), and a real, standardized distribution (right). Source: Authors.

One way to do this is to quantify the environmental information available to people and their decisions. We tested this idea through a computational model (see Netto et. al., 2017). Our agent-based model (ABM) includes action types, spatial and temporal locations, situations (represented by places of activity) and parameters of agent behavior such as the ability to search and identify social situations, make decisions based on personal guidance, and change their actions and the semantic environment itself.

For simplicity, our model uses a fictional city, a ring structure capable of representing the minimal aspects of environmental information 1 (the physical distance between places or cells) and information 2 (the differences in the social content of places or cells). The ring shape of this city allows for continuous movement through a sequence of places, eliminating centrality factors, edge effects, and the role of topology.

Our hypothesis is that (a) physical proximity, part of information 1, tends to stimulate agent interactions (Allen 1977), and (b) the diversity of activities, part of information 2, increases the potential for coordination and cooperation between agents, leading to reductions in social entropy.

In each iteration of the model, agents select and visit a specific cell within the city. Deciding which action to take can be influenced by three different conditions: (i) latent orientation, the tendency of an agent to act around a type of action based on long-term memories. This orientation is initially randomly distributed to agents, and it remains throughout the simulation. (ii) The recent action performed by the agent while he selects a place of activity to perform a new action. The influence of recent action opens the possibility of changes in orientation over time. (iii) Activity locations where agents perform the type of action. Agents select places most closely related to their latent orientations and recent actions and are influenced by these activities. Agents also influence places, but they change their content at a slower pace. This means that agents co-evolve with their semantic environment.

The model then analyzes the likelihood of finding different types of action. In the limit, when entropy drops to zero, all agents in the system would achieve the same action. In the other extreme case, that of maximum entropy, the types of action are so varied that they indicate little cooperation between the agents. We tested two types of scenarios: one where proximity between cells (one aspect of physical information) is not important to agents in their decisions (blue line in Figure 10) and another where it is important (red line).

Figure 10 shows the probability distribution of the different action types at the beginning (left) and end (right) of the simulations. The scenario in which agents choose places to go from the proximity of activity cells dramatically increases cooperation. It is as if agents learn to flex their interests by learning to coordinate their actions from the places they choose and bring them closer to certain types of action. We arrive at these results from 30 executions for each of the 125 parameter combinations (Netto et. al., 2017).

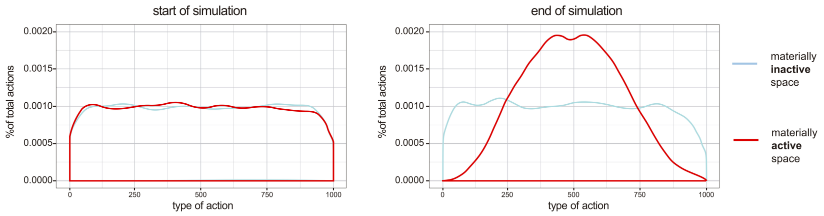

Fig. 10: Interaction entropy: The probability distributions of the action types show high entropy levels at the beginning of the simulations (left) in two scenarios: where the distance between places of activity is not considered (blue line) and where the distance is considered (line red). At the end of the simulations (right), the scenario where physical distance matters shows a convergence of agents around certain types of action, indicating cooperation from places of activity. Source: Authors.

The model shows that when agents use the criterion of physical proximity in the selection of activities, agents end up converging more frequently around certain types of action. They tend to align their actions more intensively through the informative content of places. Environmental information 'contaminates' agents. Space becomes a means to stimulate cooperation. As an information environment, the physical and semantic environment creates differences in the probabilities of interaction, helping to solve the combinatorial problem of connecting actions into a system.

6 Cities as information: concluding remarks

In this article, we attempted to understand how to analyze the information contained in the physical and semantic environment, and to understand how humans use this environmental information to coordinate their actions. Previous work has dealt only with aspects of these relationships, such as spatial information related to cognition and navigation, and synergistic networks as the basis for actions in the city, without the systemic aspect of interaction.

To link environmental information to the interaction of agents with space, we addressed three questions: (i) How do people encode and decode information from the physical environment? (ii) How does physical space convey meaning? (iii) How do people use environmental information to coordinate our actions? We explored different strands of information theory and cognitive studies to propose (a) a theoretical model of three layers of information in cities; (b) information measures in each layer; (c) an agent-based computational model to simulate how aspects of environmental information affect cooperation. More specifically:

1. We analyzed environmental information 1 in the cell arrangements from the Shannon entropy measure applied to selected empirical cases from different regions.

2. We analyzed environmental information 2 as a function of semantic diversity in local relationships between urban activities or land use. Information 2 is highly differentiated, serving as a powerful resource in the process of selecting and combining places and actions to be performed.

3. We modeled the influence of the environment on information 3 as action types in an ABM. The proximity in physical configurations (information aspect 1) and the semantic contents in space (information aspect 2) stimulate the convergence of agents around certain action types. Our model shows that aspects of environmental information in the physical and semantic space contribute to the increased coordination of agents' actions in interaction systems. The entropy of actions decreases as agents co-evolve with their environment. As far as we know, no other work integrates cognition, environment, and social systems in this comprehensive way.

Societies, as systems of interaction, need a high capacity to access and recombine information. They are 'information-hungry'. This dependence demands different types of information. Despite the addition of new information transmission networks, such as digital, which is yet to be verified empirically, environmental information seems to play an important role in the creation and coordination of our local interactions. The fact that cities preserve social information in their physical spaces and semantic structures would be an elemental part of this process, and this role deserves further investigation. Only through a structure that restricts the almost infinite combinatorial possibilities of interaction can a system acquire sufficient internal structure to enable its own reproduction.

The city would help us convert a tremendous amount of information into interaction. In fact, our cognition, environment, and actions show to have a deep connection. These systems seem co-dependent —and more. They seem to shape each other and emerge as a completely hybrid, integrated system. This integration of minds, cities, and societies could only happen through information. Information is the bridge.

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