ABSTRACT
The understanding of space relies on motion, as we experience space by crossing it in time, space’s fourth dimension. However, architects lack the necessary tools to incorporate people’s motion into their design of space. As a consequence, architects fail to connect space with the motion of the people that inhabit their buildings, creating disorienting environments. Further, what if augmentation technology changes how we inhabit space and the static built environment does not fit people anymore?

This paper explores the problem of developing a model from people’s motion, to inform and augment the architecture design process in the early stages. As an outcome, I have designed a model based on data from human-space interaction obtained through field work. First, relevant behavior was identified and recorded. Second, a metric was extracted from the data and composed by speed, the 4th D dimension as time, and gestures. Third, the original behavior was rebuilt, producing a set of rules. The rules were combined to form the model of human-space interaction. This generalizable model provides a novel approach to designing space based on data from people. Moreover, this paper presents a means of incorporating inhabitants’ behavior into digital design.

Finally, the model contributes to the advancement of people’s motion research for general applications, such as in transport engineering, robotics, and cognitive sciences.
INTRODUCTION

Ann Pendleton-Jullian (1996) states, “the crossing is not intended as a means to arrive at another place but rather an experience that changes the perceived meaning of things.” When we are still, we are not fully conscious of the space surrounding us. While moving, however, people become aware of space, interacting with the environment and others. Simulation tools that model people’s motion based on data are scarce. Moreover, models of spatial human behavior have rarely been investigated in the realm of architecture. Available tools have typically been developed to deterministically visualize figures and/or simulate pedestrians to optimize the placement of emergency exits. These tools have been mostly based on logical models, such as a sequence of assumptions, or analogue models, such as particle-flow simulations. Non-goal oriented spatial behavior, such as exploring space, has not yet been considered.

Large-scale public buildings, such as hospitals and universities, are places where people feel disoriented (Anderson 2016). Currently, architects rely exclusively on their own perceptions to improve how people inhabit spaces, due to the lack of means to address this problem. And, provided that this problem is addressed, current tools are grounded in assumptions of how humans behave in a certain context. This situation has prevented architects from being accountable for how their designs affect people’s motion. Possibly, the lack of devices to track motion has hindered the development of tools to improve navigation based on data. However, recent technology such as the Microsoft Kinect sensor has provided the means to collect data from human-space interaction, and evaluate how we behave in space. Figures 1 and Figure 3 show data visualizations of 4D trajectory data recorded with a Kinect sensor. The visualizations present cumulative data of 10 continuous hours of recording. Current devices and computer-vision algorithms provide the means to computationally model human spatial behavior through empirical research. Figure 2 presents the employed metric. The data visualizations enable the evaluation of the consistency of the behavior patterns of people in 4D.

Further, current augmented reality technology and some aspects of the internet of things are changing the way humans use space, especially public space. Augmented reality, such as the Pokemon Go phenomenon, incorporates endless fictitious elements to space, driving people to new behavior in public spaces. In a hyper-connected society events change by the second; people have access to information instantly in time, unpredictably changing their behavior as well. Yet the built environment remains static. In this paper, a data-driven approach is validated for developing a model of human-space interaction to test new designs. This model’s aim is to introduce inhabitants’ changing

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**METRIC**

**SPEED**
- No speed 0 m/s
- Slow speed 0.6 to 1.0 m/s
- Medium speed 1.0 to 1.4 m/s
- High speed 1.4 to 1.6 m/s
- Extreme speed 1.6 m/s and faster

**GESTURES**
- Change Head Direction Gesture
- Change Center of Mass Height Gesture
- Approach Attractor and Stop Gesture

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**STANDING**

- 170 TOTAL users
- 0.17 m/s avg SPEED
- 325.98 s avg TIME
- 0.8 m/s max speed
- 0 m/s min speed

**MOVING**

- 43 TOTAL users
- 1.12 m/s avg SPEED
- 1.42 s avg TIME
- 1.86 m/s max speed
- 0.81 m/s min speed

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2 The metric developed for the spatial behavior model.

3 Zoom in of the data visualization: one day of continuous data recording of 4D trajectory. Parameters were quantified per day.
behavior into the early stages of the architectural design process. The methodology seeks to prove the feasibility of developing a spatial behavioral model based on data. The identification of relevant spatial behavior for simulation, through the development of a metric, was the key element for such a purpose, presented in Figure 2. The model I have designed has the potential of disrupting architecture into a human-environment centered practice. In a broader context, such a model presents advancements in other fields beyond architectural design.

BACKGROUND

In urban design studies, simulation tools have predominantly been used for visualizing pedestrian flow. Seer, Brändle, and Ratti (2014) have presented a broad listing of the available tools for such a purpose, along with several methods for pedestrian data collection. Agent-based models, one of the methods presented in their work, have been generally considered the most accurate model for modeling pedestrian behavior. The authors used this method for developing a flow visualization of the MIT Infinite Corridor. Along with other researchers, they have used data as a means for model validation. In a similar way, the pedestrian data has been widely used for validating transport engineering simulation models. Three generic modeling parameters have been defined in transport engineering pedestrian theory: density, speed, and direction. In combination with obstacle avoidance, these parameters have been utilized to optimize people’s simulated behavior. These models have been mostly based on sequences of logical assumptions, a common practice in such a discipline. In this context, speed has been the parameter used to optimize results (Daamen, Buisson, and Hoogendoorn 2015).

Several studies in cognitive science have proposed computational models to simulate people’s behavior. For example, Jara-Ettinger et al. (2012) present a computational cognitive model of how people can learn from their environment. Roughly, their model uses a Markov decision process algorithm to independently evaluate future actions of pedestrians. Such cognitive models have frequently been considered theoretical, due to their lack of empirical data describing people’s analogous spatial behavior. Consequently, the research presented in this paper is essential for bringing forth the possibility of validating and grounding this type of computational model in data.

In the context of architectural design, the subject of modeling people’s spatial behavior data has not been fully explored. Architectural studies of people’s motion, despite being based on data, have tended to focus on qualitative insight for the projective process. For example, Chŏng and Branzell (1995), developed a “study of how different persons react when exposed to different full-scale objects.” The researchers quantified the qualitative impact that different spatial settings had on people.

To the best of my knowledge, a model based on data has not been developed, either in architecture or in any related discipline. Neither has a model that focuses on providing insight for architectural design been proposed. Agent-based models have been a recurrent option for facing the challenge of representing how space is used. An event-based approach has proven to be
feasible, but it has not yet been based on data from humans (Simeone 2012). A similar approach is to use film dedicated software for crowd simulation in urban design (Aschwanden, Halatsch and Schmitt 2008). Ferreira de Mello, and Duarte (2012) propose a shape grammars approach to choreographing human spatio-temporal behavior without including the data collection component.

METHODS

The methodology translates dynamic data from human-space interaction into rules. The development of the generative model consisted of four steps:

Step 1: Identify and Record Relevant Behavior
Relevant behavior was identified and recorded. Data was collected from people’s motion in semi-public indoor spaces with digital devices. Three university campuses from different countries, including the USA, Chile, Italy, and Colombia, were selected as data collection locations in order to assess the results at a macro level. The datasets were produced in real-world conditions; people were recorded without them knowing. The selected areas to record were identified as generalizable architectural features. For example, spaces like a staircase, a corridor, or the area around an entrance are standard elements of practically every building. The selected recording devices were Microsoft Kinect sensors and video cameras. Kinect datasets cover a triangular area of 4 meters, and video data covers approximately 22 square meters. The advantage of using Kinect is that its software can recognize a 25 joints skeleton from a person’s relative position in four dimensions. The produced datasets are trajectory data from a person’s head and center of mass. To record and analyze skeletal data with Kinect, I developed a custom script. To analyze the video footage, I manually counted the number of gesture occurrences, and used computer-vision algorithms to extract the position of such gestures. To assess the quality of the data, I developed visualizations in two and three dimensions.

Data Collection in Time
During 2015 I collected data from approximately 8,000 students at the different locations described in the datasets from Tables 1 and 2. For this task, I obtained the “Human Subject Research Certification.” For each recording, large signs were posted to inform people that the data collection was taking place. Table 1 presents the list of the datasets recorded with Kinect, in five different locations for continuous periods of time. In the case of the Media Lab building’s lobby, I collected data for one day over 3 consecutive weeks. Table 2 presents the data recorded with video camera for continuous periods of time as well. During 2013, the Media Lab Responsive Environments group recorded data with 25 Kinect sensors, in different locations of the Media Lab Building, for the entire year. Eight locations were selected from the data and extracted a month-long dataset from each.

Figure 4 displays visualizations of Kinect data from the Media Lab Building. The color of the points changes every time the trajectory of a new person starts. The 0,0 coordinates are on top of each image and designate the position of the Kinect. It is possible to observe that larger colored areas appear in the areas
where people spent more time. An interesting pattern to observe is that people choose to walk at a consistent distance from objects. This pattern is present in locations recorded by Kinect number 333 and number 140.

**Table 1** Datasets recorded with Kinect sensor 2015

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Location</th>
<th>Hours</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>k1</td>
<td>UniLab Corridor</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>k2</td>
<td>MIT Lobby 10</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>k3</td>
<td>Corridor</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>k4</td>
<td>MIT Lobby 7</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>k5</td>
<td>Media Lab Lobby</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>k6</td>
<td>UC Vestibule</td>
<td>8</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 2** Datasets recorded with video camera 2015

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Location</th>
<th>Hours</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>v1</td>
<td>MIT Lobby 7</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>v2</td>
<td>Media Lab Lobby</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>v3</td>
<td>MIT Infinite Corridor</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

**Step 2: Extract a Metric From the Data**

The metric was developed by observing the frequency of motion correlated with an architectural feature. At this stage of the research, I concluded that speed, time, and gestures are sufficient parameters to describe human-space interaction in 4D in a given architectural setting. The metric is presented in Figure 2 at the beginning of the paper. In contrast to previous works, speed is considered as an approach towards space, rather than as an optimization parameter. The time that people spent in a location is understood at the level of occupancy. The conceptualization of “spatial gesture” is an important advancement of this paper. I found that we perform bodily gestures towards architectural features in time. A spatial gesture consists of a combination of changes in bodily motion in relation to a spatial feature in 4D. For example, a spatial gesture is observed when a person changes their gaze towards an architectural element such as the upper floors of a multistory atrium. This concept describes explicit behavior motivated by the architectural features. To conclude this stage of the process, I calculated statistics from the data in each of the locations, for each of the parameters of the proposed metric.

**Step 3: Develop the 4D Rules**

The rules were formulated by connecting form/spatial attributes with motion. All the parameters corresponding to a certain location were recombined to reconstruct each behavior as a rule. The rules were defined graphically, and the quantified parameters were added as qualifiers. I grounded the general development of the rules in shape grammar theory. Shape grammars are rule-based systems for describing and generating designs, and are distinctive for their highly visual approach. (Knight and Stiny 2015).

**Step 4: Generate the Model**

The rules of the model describe the behavior of people in correlation with architectural features. The rules group represents a model as a whole. These rules have no established order and can be recombined as needed. The sequence will depend on the design that is being developed. By recombining these sequences, a new expected behavior can be produced to provide insight into how people might move inside a newly designed space.
RESULTS

Statistics

Figure 9 shows the results obtained from Kinect data. The survey measured the movement of approximately 8,000 pedestrians in semi-public spaces. These results are validated by the accuracy of the Kinect sensor, which records motion to the millimeter scale. The baseline for walking speed is 1.4 m/s, as presented by the “Design Manual for Roads and Bridges” (Highways Agency 2011). Speed and time, the 4D dimensions calculated from Kinect data, are presented together to show their correlation.

These results strongly suggest that pedestrian behavior is analogous among various locations. In three of these locations, the average speed is almost the same. These three locations are spaces for walking only. In the other two locations the average speed is lower, yet the results are very similar if we compare only these two values. These two locations present a similar architectural configuration. Both spaces are vestibules where people can pass through as a corridor, walk outside the buildings, or do activities. Images of both spaces are included in the appendix.

From the data, it can be inferred that data can be transposed from one social group to another. It is evident that the architectural layout has an effect on people’s motion. The results are coherent insofar as the environment where the data was recorded is considered.

Figure 7 presents the percentage of gestures captured with video footage in each of the locations. The survey quantifies common spatial gestures happening in semi-public spaces from approximately 1,600 people. The position of these gestures was obtained with a computer-vision algorithm called “Background Subtraction,” implemented in the Processing software. The most significant result presented a quantification of the “look up” gesture as recorded at the Media Lab lobby. This result exposed that more than half of the observed people changed their gaze when walking from a low ceiling area and looked up towards the openness of the multistory atrium. The complete analysis of the gesture can be found in Gonzalez (2015).

Rules

The developed rules are basic pieces of a larger generative model. Ian Bogost writes, “The complexity of these systems is generated by the cooperative effect of many simple identical components... (Generative models) offer a way to understand complex systems by breaking down large scale behavior into simple generative rules” (2008, 94). When combined in a new sequence the rules generate the description of a new behavior.

The rules were formulated with breadth of search as the first criterion, privileging the collection of as many different behaviors, in relation to as many architectural features as possible. Speed is color coded in order to understand how people approach space. Gestures are divided into three basic rules: change of gaze, change of center of mass height, and the gesture of purposely approaching a spatial attractor. For example, seating is translated into a change of the height of the center of mass. Finally, time reflects the periodicity of the rule, framing the impact of the rule in time. Figure 8 describes one rule in detail.
identified reliable principles, providing a foundation for the analysis of human spatial behavior in broader terms.

In addition, the spatial behavior metric I presented is a framework that enables the manipulation of a complex 4D phenomenon. The concept of spatial gesture has a unique potential for understanding human-space interaction. Unprecedented, this metric is a key component for future research. Further, I will subsequently include shape and direction parameters in the analysis. Regardless of the inherent limitations that every representation has, a model as proposed in this paper has the capability of enabling designers to characterize human-space interaction in a tractable way in order to enhance design, and possibly create more orienting and 4D-augmented spaces.

Speculation about applications for design exposes three possible explorations. The first application is to provide real-time feedback on how people would navigate a complex space. The feedback is analogous to radiation and lighting evaluation. A second exploration is to use simulated motion in virtual reality combined with motion tracking. The setting would enable a person to interact with simulated people and experience new designs while moving through the space. Buildings could then be evaluated as they would be when inhabited. A third speculative application is at the level of participation; with the use of augmented reality, new designs could be used to augment real spaces for people to experience them. Real-time motion tracking is compared with the proposed model to evaluate the new design. Such explorations propose that by providing input of the behavior of people in time, architects can design in 4D. The human-space interaction model provides specific insight for designers, as the main focus is to model people’s spatial behavior in correlation with architectural features.

CONCLUSIONS
So far, the data have shown that it is possible to transpose results from different cultures at the macro level. The locations were analogous and produced highly similar results. By dissolving the constraint of respecting the data’s origin, this outcome opens new paths for simulating people’s motion. The model I have designed materializes the possibility of incorporating people’s motion in the process of digitally designing space. For the future of the discipline of architecture, this research proposes to include people’s behavior in the design process. It intends to push from form-centered design to human-environment-centered design that includes the fourth dimension, time, thus disrupting the current state of the art.

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REFERENCES


IMAGE CREDITS

All drawings and images by the author.

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