Extracting Cognitively Ref 024

Relevant Measures from Environmental Models

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Abstract
Space syntax and other models of environmental form are of great relevance to spatial cognition research on how people perceive, explore, and learn their physical surroundings, whether those surroundings be building interiors or entire cities. To run such a "human-subjects" study requires both behavioral measures (e.g., a person's accuracy at pointing toward an out-of-sight landmark, the number of times a person walks down a given route segment) and environmental measures (e.g., the visual entropy of the open space around that landmark, the axial integration of that route segment). Behavioral measures are well documented in the psychological literature, although many remain somewhat inaccessible to the space syntax community, buried in specialist journal articles. Likewise, the space syntax community has developed a wide range of measures that can be extracted from a model of environmental form, many similarly buried in the proceedings of this symposium. In this paper, I offer a rough classification for behavioral measures and for environmenttal measures, suggesting when each type of measure is most appropriately used; along the way, I discuss how the behavioral measures and environmental measures can be best paired for meaningful analysis. In some cases, studies have already been performed that combine certain measures; I briefly review those. In other cases, there is little prior work to cite in other words, fertile territory for further research on the interaction of internal human cognitive processes and the physical form of the external world.

1. Introduction

Space syntax's modeling techniques offer an ever-growing assortment of quantitative measures for an environment's physical form. Environmental psychology's research literature describes a similarly wide range of quantitative and qualitative measures for a person's behavior and cognition related to their environmental surroundings. The overlap between the two fields is clear: a "toolkit" for analyzing environments, on the one hand, and a set of theories and findings for carefully studying people, on the other. Certainly there are theoretical disconnects between the two fields (for example, compare Hillier, 2006, and Montello, 2007). Yet there is also a more practical concern, one that must be considered by each researcher pairing environmental models with behavioral studies: extracting cognitively-relevant measures from environmental models.

Here is an example: A space syntax researcher has modeled a university campus using *visibility graph analysis* (a.k.a. VGA; Turner, Doxa, O'Sullivan, & Penn, 2001). For each point in the "open" space on the campus, she can produce a visual entropy value (not to mention many other measures). An environmental psychologist has also studied the same campus. He took participants in his study to a number of locations around the campus, stood them in predetermined locations, and asked them to point toward campus buildings that were well known but ought of sight. He has data on people's spatial knowledge for aspects of the campus; she has data on the physical form of the campus. Which measures can they use from her VGA to account for environmental effects in his behavioral data?

Underneath this straightforward question are a number of lurking issues. The participants' pointing responses measure directional knowledge from the location they stand toward a target building. The VGA can easily produce measures for the former location because the participants stand in "open" space. Extracting measures for the latter is more complicated because buildings are, as "closed" space, left empty in VGA.

The first step in performing VGA is to lay down a grid of cells—this raises another complicating issue. The resolution of this grid will affect the output measures, which will in turn affect comparisons with behavioral data. Our space syntax researcher needs to set the resolution of her VGA model so that it's both computationally doable on her computer and so that the resulting measures are "psychologically valid." A VGA with grid cells of 25 meters square does not seem psychologically valid when a person, standing outside, pointing toward an out-of-sight building fills a space closer in size to 1 or 2 meters square.

Fortunately, neither of these issues is novel. The concepts of *geographic information science* and the techniques of *geographic information systems* (a.k.a. GIS) have already addressed both. One option in the case of the empty buildings is to draw a *buffer* around each building, capturing the VGA grid cells within a certain distance of its outline, and to then extract measures from this surrounding area (Longley, Goodchild, Maguire, & Rhind, 2005, Section 14.4.1). In the case of the resolution question, an option is to run models at different resolutions and compare results (c.f. Dietzel & Clarke, 2004).

Geographic information science also offers us another valuable asset: a neutral language for discussing models of environments' physical form. This language of *points*, *lines*, and *polygons*, of *objects* and *raster fields* can be understandable to space syntax researchers and environmental psychologists alike—sidestepping that perennial issue of whether one buys into the theoretical edifice of the other. This approach also allows us to consider space syntax, with its venerable *axial lines* (Hillier & Julienne Hanson, 1984, Chapter 3) and its more recent *segment maps* (Hillier & Iida, 2005), alongside other traditions like *isovist analysis* (Benedikt, 1979; Tandy, 1967), all under the umbrella of *environmental modeling*.

In this paper, we will briefly review the research topics and measures of environmental psychology (in Section 2) as well as the model and measurement types of environmental modeling (in Section 3). Those rough typologies will allow us to consider possible pairings of behavioral and environmental measures (in Section 4). Some of these pairings have already been attempted by researchers; others have yet to be considered. The framework put forth in this paper will enable us to make a few preliminary comments on fruitful combinations of the psychological and the environmental, and this framework will also, ideally, be of future use to researchers further elaborating the connections between behavioral and environmental measures.

2. Environmental Psychology: Research Topics and Measures

The question of how people and environments interact is overwhelmingly broad. Researchers have gained traction by pursuing narrower topics, such as *navigation* and *spatial knowledge*. Environmental psychology of course includes many other research topics—affect and preference, for instance. Navigation and spatial knowledge are worth focusing on because they are lower-level processes that underlie where people travel and what they remember, and they depend on both perception and cognition. We will review the two topics and the behavioral measures most commonly used to study each.

First, navigation:

"*Navigation is coordinated and goal-directed movement through the environment by organisms or intelligent machines. It involves both planning and execution of movements. It may be understood to include the two components of locomotion and* wayfinding*. Locomotion is body movement coordinated to the local surrounds; wayfinding is planning and decision making coordinated to the distal as well as local surrounds." (Montello, 2005, p. 257; italics are mine)*

Successful locomotion—reaching a target and avoiding any intervening obstacles—depends on the accurate perception of one's immediate surroundings, which for most people comes through vision. They may consciously select their destination, but the process of reaching that destination involves a mix of conscious and unconscious processes; for example, steering using the eye's perception of directionality, known as *optic flow*: (Warren, Kay, Zosh, Duchon, & Sahuc, 2001)). Consider agent-based models in light of this distinction (e.g. Turner & Penn, 2002). If an agent selects its next location based simply on the points visible in its immediate surroundings, then that agent is modeling locomotion but not wayfinding. The agents do not make plans for reaching out of sight destinations.

Whether it is locomotion or wayfinding that is being studied, researchers most often measure and record the path that a human or an agent takes through an environment.[2] What differs is the resolution at which that path must be measured. In their study of locomotion, Warren et al. (2001) tracked participants' head position with a root mean squared error of 4 mm and their orientation with a root mean squared error of 0.1 degrees. This level of precision and accuracy requires elaborate equipment: a grid of ultrasonic transmitters hung from the laboratory ceiling and a receiver worn on participants' heads, which also uses inertial measurements to provide further correction. And in this case, such precision and accuracy is required to study the minute maneuvers of locomotion in terms of translations, rotations, and speed changes.

Contrast this locomotion study with a study of wayfinding. Cornell, Heth, and Rowat (1992) guided children and adults, one by one, along a route through a university campus. Some participants were provided with strategies for learning the route, while others were provided with no additional information. After completing the guided walk, participants were asked to retrace the route back to the start point. The question is how participants' ages and the instruction they received affected their performance at retracing the route. The outdoor setting of this study did not afford the same tracking precision and accuracy as Warren's lab, and fortunately that was unnecessary. An experimenter could follow the participants, trace their routes on a campus map, and record when they mistakenly turned off the route. This level of precision and accuracy is appropriate for studying wayfinding.

Say our fictitious space syntax researcher, from the introduction, is trying to relate her VGA model to the path people take through that environment. When determining the resolution at which to construct the VGA model, she will want to consider whether she and her environmental psychologist colleague are studying locomotion or studying wayfinding. In the process, she will also want to consider the level of precision and accuracy of their tracking measurements.

Wayfinding does not even need to be studied in situ. Useful data on people's route planning and decision making can be collected at a desk, with pencil and paper. Bailenson, Shum, and Uttal (2000) asked participants to select and highlight routes between two points on a paper map. With this data, they concluded that participants chose their routes largely based on the straightness of each route's initial segment. If our space syntax researcher were collaborating on this project, she would be able to resolve participants' routes to individual streets or walkways.

In the most widely used research method of environmental psychology, the paper map is dispensed with—participants receive only a blank piece of paper and are asked to draw their own map. *Sketch mapping* is not a direct output of people's "cognitive maps," but it does provide a partial "readout" of their spatial knowledge. From firsthand experience and controlled studies alike, we know that spatial knowledge is systematically distorted (Tversky, 1992). People do not necessarily remember the distance from Point A to Point B as the same distance as Point B to Point A; this is a distance asymmetry (e.g. Sadalla, Burroughs, & Staplin, 1980). Road intersections are remembered as more orthogonal than they in fact are; this is the application of a simplification heuristic (e.g. Byrne, 1979). Distortions like these are certainly evident in sketch maps that are analyzed in a qualitative manner (e.g. Appleyard, 1970) or a quantitative manner (e.g. Buttenfield, 1986). That said, sketch mapping is only one method by which spatial knowledge can be measured and it is a highly problematic method at that.

Spatial knowledge can also be measured in a more piecemeal fashion. In our initial example, our environmental psychologist had participants pointing toward out of sight landmarks. Directional knowledge can be measured like this—in situ—or in a lab setting (Waller, Beall, & Loomis, 2004). Likewise, distance knowledge can be measured by a variety of methods (Montello, 1991). Quantitative measures like direction and distance estimates may not produce the striking illustrations of sketch maps, but when we pair those behavioral measures with environmental measures, other advantages will become evident.

3. Environmental Models of Physical Form: Types of Models and Measures

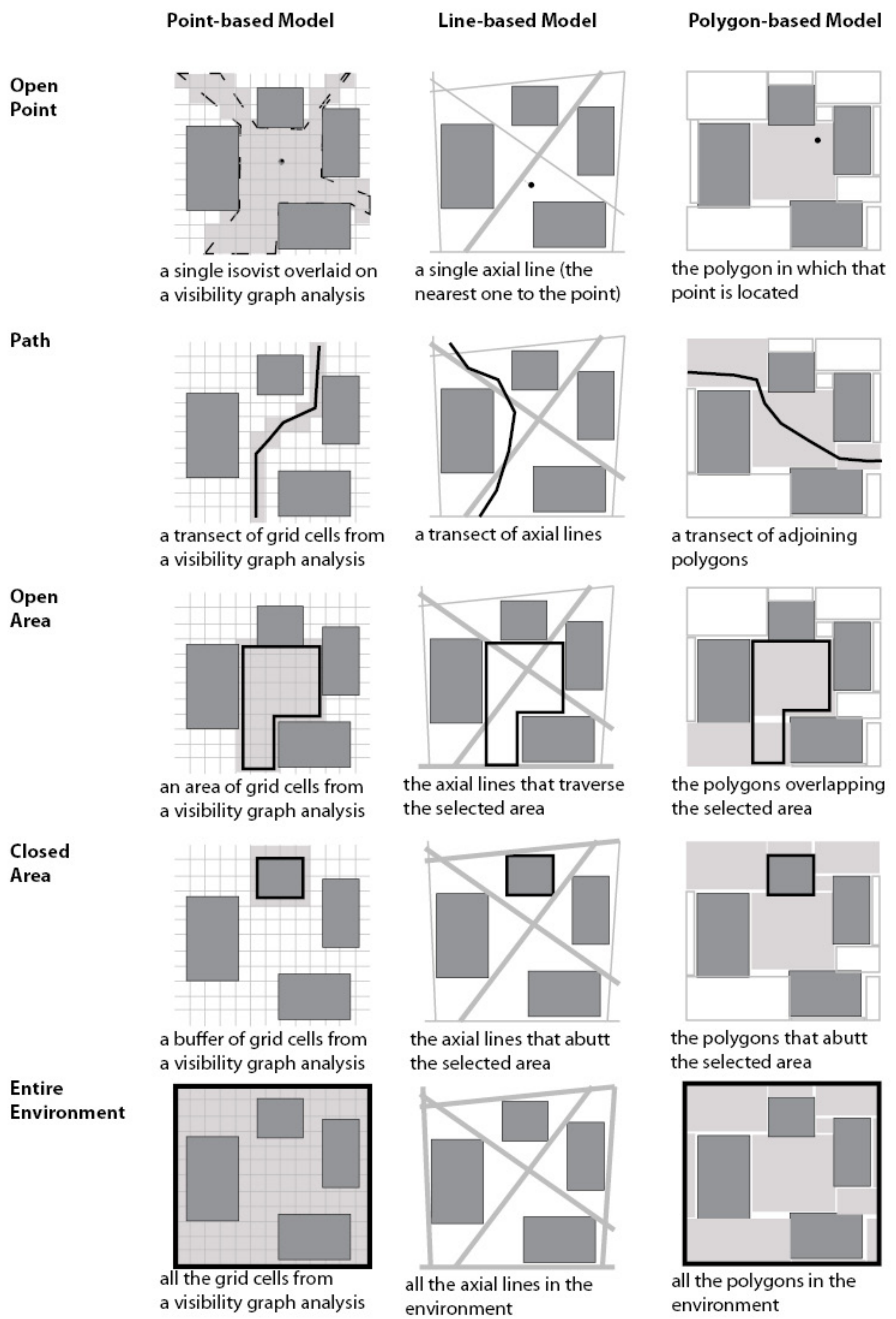

Figure 1

Three types of models (columns) and five types of measures (rows). The point, path, or area of interest is indicated in black. VGA grid cells and polygons to be measured are indicated with gray fill, and the axial lines to be measured are indicated in bold

The notion of *spatial primitives*—that is, basic units with which geographic information is represented—is important in GIS and geographic information science. In the case of GIS, geographic information is stored in data structures composed of raster fields or of point, line, and polygon objects (to cite the two most widespread approaches). In the case of geographic information science, these spatial primitives are used to discuss representational assumptions and computational limitations. For example, a raster field like the grid of a VGA lends itself to certain analyses, certain ways to represent vagueness, certain methods of processing, and so on. Using this language, let us consider the various types of environmental models to be found in space syntax and related traditions.

Because VGA is based on isovists, its spatial primitives are points, specifically the points from which visibility is computed. To make VGA computationally tractable it's turned into a discrete computation by laying down that uniform grid of cells—a raster field in other words.

Axial maps and segments maps are both, clearly, built of line objects. An axial line is, more or less, used to capture and represent a sightline. A segment is, more or less, used to capture and represent a possible line of movement between two choice points.

Another definition of an axial line is that it is the longest possible line that crosses at least two convex regions of space. These convex regions of space—rooms in a building of rectangular rooms, say, or quadrangles on an idealized college campus—are polygons. A justified-graph (a.k.a. *j-graph*; reviewed by Bafna, 2003) is one way of representing these polygon objects. Those polygons that are adjacent to each other and connect, like two rooms connected by a door, are also connected in the j-graph.

From these three types of environmental models, a number of different types of measures can be extracted, also point-, line-, and polygon-based. A measure can be extracted for a point in "open" space; the point where a person stands as they point to an out-of-sight landmark, for example. A series of measures or an aggregate measure can be extracted along the line segments of a path; the route a person walks, for example. A series of measures or an aggregate measure can be extracted for a polygon of "open" space or for a polygon of "closed" space. In the former case, this might be a city square; in the latter, a building. Recall that a technique like buffering is necessary to extract measures for "closed" spaces. Finally, measures can be extracted to describe the entire environment.

As Figure 1 shows, a good number of combinations of model type and measure type are possible. We have not even considered the various measures that each environmental modeling technique produces. For one point in "open" space, a VGA model can provide measures like visual control, visual controllability, visual integration, and visual entropy, to name only a handful. All these measures fall into a taxonomy of their own and each have a psychological relevance of their own—that, however, is a large topic best left to another paper.

4. Behavioral and Environmental Measures Paired

What we can consider in this paper is how these combinations of model type and measure type are best paired with behavioral measures. Table 1 lists a selection of published studies; it is certainly incomplete. Note that these are all studies of individual participants. The space syntax literature includes many more studies of aggregate populations—such as those based on the number of pedestrians observed at "gate" points along sidewalks—but drawing conclusions about the behavior patterns and cognitive processes of individuals from that aggregate data can be thorny. Let us consider a few representative studies of individuals,

Wiener and Franz (2005) studied locomotion using point-based isovist and VGA models. Participants explored a virtual environment that was displayed on a large computer screen and that they could move around using a joystick. Their primary task was to "move to the position that maximized the isovist area (best overview place) and to the position that minimized the isovist area (best hiding place)" (p. 49). Performance at this task was predicted by both point-based measures of the isovist at the respective target position and polygon-based measures of the entire "open" space of the environment. The combination of visibility measures that significantly predicted performance tells a story about which particular environmental properties people use to find overview places and hiding places.

	Point-based Model	Line-based Model	Polygon-based Model
Locomotion	(Wiener & Franz, 2005)		
Wayfinding	(Conroy, 2001) (Hölscher et al., 2006) (Meilinger, Franz, & Bülthoff, 2009) (Peponis, R. C. Dalton, Wineman, & N. Dalton, 2004)	(Haq & Zimring, 2003) (Hölscher et al., 2006) (Peponis, Zimring, & Choi, 1990)	(Hölscher et al., 2006)
Spatial Knowledge	(Meilinger et al., 2009) (Dara-Abrams, 2008) (Davies, Mora, & Peebles, 2006)	(Dara-Abrams, 2006) (Kim & Penn, 2004)	

Table 1
A selection of studies that pair behavioral and environmental measures.

Wayfinding has been the most popular research topic in environmental psychology to be studied in combination with environmental models. This is a natural continuation of space syntax's aggregate studies of "movement economies." Hölscher, Brösamle, and Vrachliotis (2006) studied wayfinding in a real-life, multi-story building. They asked participants, some of whom had prior experience with the building and some of whom were new to the building, to find certain indoor locations. An experimenter followed each participant with a video camera and later drew the routes on a floor plan of the building. These behavioral results were compared with a point-based VGA model and a line-based axial map. In some sense, a polygon-based model was also used, as they extracted visibility measures for each participant's path by chunking segments of the building's "open" hallway space into convex polygons. These environmental and behavioral measures together suggested that inexperienced users of the building chose to travel paths more visually connected and more visually integrated, but perhaps less direct than those taken by experienced users.

Wayfinding is relatively straightforward to study by measuring observable behavior. We have already discussed a few of the many ways to "readout" spatial knowledge. Pairing those behavioral measures with environmental measures can be tricky. Recall the example we began with, a VGA model of a university campus and a data set of participants' direction estimates from point-like locations to out-of-sight buildings. Dara-Abrams (2008) ran such a study. Environmental measures for the "closed" areas of the buildings were extracted using the buffer process we discussed earlier. Comparing that set of visibility measures with the behavioral data suggested a pattern of environmental properties that characterize the locations of buildings people remember more accurately.

These are only three of the studies listed in Table 1; the others are equally relevant and worth consulting.

5. Conclusion

In this paper, we have addressed the question of how to extract cognitively-relevant measures from an environmental model. We briefly reviewed locomotion, wayfinding, and spatial knowledge as three topics in environmental psychology that call for the use of environmental measures. We also reviewed environmental modeling in terms of the concepts of geographic information science. In the process, we created a simple (perhaps even simplistic) classification of environmental models into point-based, line-based, and polygon-based. This classification allowed us to consider existing studies that have paired behavioral and environmental measures, even if we only discussed a small, representative sample.

This classification points toward many opportunities for future research. A growing body of work addresses wayfinding using environmental measures, but locomotion and spatial knowledge have received less attention. Spatial knowledge, in particular, will likely continue to be both a complicated and a fruitful application of environmental measures. On one end, the various options for spatial knowledge "readout" produce behavioral data that is appropriate for comparison with certain types of environmental measures but not others. On the other end, there is the question of what each particular environmental measure means in psychological terms—for instance, what story does visual entropy tell about a location and someone's memory for it? Considering the many measures provided by VGA, by axial maps, by segment maps, and so on, is an appropriate next step, one that can build on the foundation we have discussed here.

6. Notes

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2 Since agents are models of human processes rather than environmental structures, agent-based models will not be discussed in the next section on environmental modeling.

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