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COGNITIVE AGENTS AND PEDESTRIAN-ORIENTED REDEVELOPMENT

by

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DISSERTATION ABSTRACT

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Walking is one of the most commonplace forms of human expressions, yet the forms, motivations, and practices of walking vary greatly and are often at odds with dominant discourses in urban and transportation planning. As interest in pedestrian-oriented studies continues to grow, there is danger that dominant discourses will continue to reinforce the framing of pedestrians and the practices of walking as slower moving versions of the private automobile and ignore deeply embedded emotional, personal, and cognitive aspects. As such, understandings of pedestrian transportation and human agency during walking must be explored in increasingly human-centered terms in order to understand how changes to the material environment actually impact people and daily practices. The purpose of this dissertation is to give considerably more attention to the human elements of walking by creating a set of new theoretical and practical frameworks for deeper representations of the pedestrian in the urban space and within a larger transportation system. The three articles presented in this dissertation outline an alternative, human-centered representation of the pedestrian, providing theoretical, methodological, and practical solutions to conceptualize how soft variables such as emotion, motivation, and especially cognition influence the practices of walking.

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For my partner, my parents, and my pets and the unconditional love you show me

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INTRODUCTION

"Perhaps walking is best imagined as an 'indicator species,' to use an ecologist's term. An indicator species signifies the health of an ecosystem, and its endangerment or diminishment can be an early warning sign of systemic trouble. Walking is an indicator species for various kinds of freedom and pleasures: free time, free and alluring space, and unhindered bodies"
– Rebecca Solnit, 2000

Walking is one of the most basic human expressions, so commonplace and familiar in fact that we engage it daily with little thought or concern. Solnit (2000) describes walking as "how the body measures itself against the earth" (31), while De Certeau (1984) describes pedestrian encounters in saying, "(t)he act of walking is to the urban system what the speech act is to language or a statement uttered" (97). Yet the seeming simplicity of walking in fact masks a complex entanglement of deeply personal and social, physiological, and cognitive practices that make up human movement. Walking can be a form of embodied social capital (Jacobs 1961), and a way to transcend the trappings of political and social systems (Thoreau 1862). Walking can be an avenue toward deepened intimate and personal connections to place (Tuan 1974), or a form of resistance against the structures of orthodox planning (De Certeau 1984).

While the pedestrian has long been marginalized in urban planning and policy in favor of the automobile (Southworth 2005), walking is increasingly understood to be a local solution to a range of global problems, often framed as "a simple, practical-minded solution to a host of complex problems we face as a society, problems that daily undermine our nation's economic competitiveness, public welfare, and environmental sustainability" (Speck 2012: 11). Indeed, Solnit (2000) frames walking as an indicator species of urban health, and Speck (2012) claims, "the pedestrian is an extremely fragile species, the canary in the coalmine of urban livability" (10). In light of such shifts in perception, there is a growing need for changes in urban infrastructure, and pedestrian mobility and understanding practices of walking is currently a high priority in both research and policy-oriented agendas (Middleton 2011).

Yet the forms, motivations, and practices of walking vary greatly and are often at odds with dominant discourses in urban and transportation planning. As interest in pedestrian-oriented studies continues to grow, there is danger that dominant discourses will continue to reinforce the framing of pedestrians and the practices of walking as slower moving versions of the private automobile and ignore deeply embedded emotional, personal, and cognitive aspects. As such, understandings of pedestrian transportation and human agency during walking must be explored in increasingly human-centered terms in order to understand how changes to the material environment actually impact people and daily practices. The purpose of this dissertation is to give considerably more attention to the human elements of walking by creating a set of new theoretical and practical frameworks for deeper representations of the pedestrian in the urban space and within a larger transportation system.

Despite increased attention to pedestrian practices, disconnections between policy-centered and human-centered aspects of walking have continued to grow. Policy-centered research typically focuses on the technical components of the transportation system, prioritizing efficiency and network structure at neighborhood or citywide scales. Human-centered research tends to focus on performative practices, underlying cognitive processes, and the experiential dimensions of walking. Cascetta et al. (2015) argues the competing discourses highlight the 'wicked problem' of transportation planning, calling instead for approaches that put social and technocratic discourses into conversation with each other to give proper consideration to both aspects of the system.

In addressing such disconnects between policy-centered and human-centered discourse, many scholars advocate for a behavioral geographic approach to conceptualize and formally represent pedestrians in the environment (Golledge and Garling 2001). While many policy-centered representations tend to treat the pedestrians as rational agents, behavioral geographers argue instead that the observable behaviors and patterns of movement do not indicate generalizable rules about human-environmental interactions, but rather reflect individual differences in cognitive capabilities, emotional states, and embodied motivations (Golledge and Stimson 1997). Lynch (1960) details the variance in environmental knowledge acquisition from person to person, illustrating how internal representations of the environment are a valuable construct when trying to understand individual perceptions and the resonance of different types of environmental features. Raban (1974) extends this discussion, highlighting how linkages and disconnects between concrete materiality and cognitive representations reveal the vast array of individual experiences and encounters in pedestrian practice. Whyte (1988) complicates the pedestrian further, calling attention to human cognitive and physiological processes propelling in the seemingly simple act of walking:

> The pedestrian is a social being: he is also a transportation unit, and a marvelously complex and efficient one. He is self-contained, self-propelled, and moves forward with a field of vision about 100 degrees wide, further widening this with back-and-forth scanning movements to almost 180 degrees. He monitors a host of equations: two crossing patterns at left front, 290 feet a minute, three on the right, angle on the cars 30 degrees and closing, a pair abreast dead ahead, a traffic light starting to flash DON'T WALK. In fractions of a second he responds with course shifts, accelerations, and retards, and he signals to others that he is doing so (56).

Many urban and transportation redevelopment projects hinge on the assumption that a particular set of changes in the built environment will result in a set of predictable behavioral response among the population. Alternatively, a behavioral geographic approach embraces individual differences and subjectivities, working instead to link observable spatial behaviors to internal variables such as the accuracy of spatial knowledge acquisition, abilities to encode environmental stimuli influences, and map-reading abilities (Montello 1998; Lobben 2004). With a behavioral approach, pedestrian-oriented transportation planning becomes less about trying to identify generalizable rules about the spatial configurations of pedestrian spaces and more about exploring the range of design possibilities that will be inclusive and meet the needs of a diverse range of people within the population.

Over the past decade, numerous strategies for transforming transportation infrastructure have encountered varying degrees of success upon implementation. Increased financial and political pressure on local governments surrounding redevelopment has created a need for tools to evaluate how changes to the built environment will impact the behaviors of citizens. Agent-based models, which are often portrayed as capable of highlighting the relationship between individual-level decisions and system-wide patterns (O'Sullivan and Perry 2013), can respond to this need by providing a computational framework to understand the relationship between changes in pedestrian infrastructure and human spatial behaviors. Unlike inferential statistical models, agent-based models allow for more flexible and dynamic representations of individual behavior and can provide insight into how individual human behaviors produce large-scale spatial patterns. Despite the potential of agent-based models in public discourse, the method remains on the fringe of transportation discourses and pedestrian-oriented policy discussions. This absence is largely due to scientific inquiry on the pedestrian often frames the individual as a rational agent, one who behaving in self-interest towards a defined goal, often reducing the very human aspects of pedestrian movements – emotions, cognition, performance, and social aspects – to largely de-humanized and predictable behaviors. These assumptions of rationality has, in many ways, made the development and public use of agent-based models limited to instances in which coarse and generalizable observations are required, namely evacuation and wayfinding models. Agent-based models can provide an alternative to these coarse representations however, and provide social science and public policy researchers a tool to represent the agent in more-than-rational terms and the embrace individual agency into computational and repeatable metrics.

To untangle this issue and provide a strong framework for representing pedestrians, this dissertation explores how human-centered dimensions of walking can be incorporated into both computational modeling and more broadly into policy-centered transportation discourses, with a particular focus on individual cognitive processes and how people perceive and understand the built transportation environment. The three subsequent chapters investigate issues in pedestrian representation from theoretical, methodological, and practical modeling approaches, each with the larger goal of understanding how deeper, human-centered approaches to the pedestrian can inform policy-centered transportation discussions. The dissertation is guided by the following research questions:

1. What are the philosophical roots of the rational agent representation and how does this framework influence current transportation planning policy?
2. How can data generated about individual differences in environmental cognition be used in the development of a pedestrian movement model?
3. How does the development of agent cognition aid in the credibility of real-world pedestrian movement models?
4. What key design variables in transportation redevelopment projects emerge from a cognitive pedestrian movement models?

In order to comprehensively investigate the role of cognition in human movement and gain insight into how a deeper understanding of individual and internal processes during movement can inform pedestrian-oriented redevelopment, this study blends methodologies from behavioral geography, environmental psychology, and complex system science to integrate issues in transportation policy, human cognition, and computational modeling. By employing an innovative agent-based modeling approach, this research works to understand the relationship between real-world spatial behaviors and scenario-driven transportation redevelopment, especially in regards to pedestrian movement and street redesign practices. In doing so, this dissertation as a whole addresses fundamental gaps in both theoretical and computational representations of the pedestrian, with each chapter providing critical insights into debates surrounding pedestrian-oriented urbanism and uses of public space.

Chapter 2, “Pedestrianism and the more-than-rational agent” challenges the concept of rationality in the representation of pedestrians in the transportation system. This chapter begins by acknowledging how new approaches to measure and understand human behaviors in cities position the pedestrian as rational decision-making agents within the transportation system. It then traces the roots of the rational agent to neoclassical economics and the *homo economicus* social model, critiquing how rational choice theory is often extended or spatialized into the transportation system with structural models of network optimization that characterizes movement within the system with measures of space/time efficiency. Specifically, this spatialization of the rational agent relies on a rather narrow set of human-object interrelations outlined by the theory of affordances and the framing of environmental objects as hard, fixed, and immutable features. The chapter continues by illustrating the ontological differences between the two predominant types of transportation models – structural configuration models and human-centered behavioral models – employing findings from a route planning study to illustrate disconnects between human-centered perceptions of space and institutionalized conceptions of space (Lefebvre 1991). The chapter concludes by introducing a formal framework to represent pedestrian agents in the urban environment that moves beyond rational subjectivities and makes room for softer human-environmental encounters and performative engagements in transportation planning discourses.

Chapter 3, "Ecological validity of human representations in agent-based models" takes a decidedly more methodological approach to advance the representation of human pedestrians in computational models. Agent-based models allow for heterogeneous representations of human entities that can be embedded with a range of emotional, social, and wholly more-than-rational behaviors (O'Sullivan and Perry 2013). Cognitive variables are of particular importance, as the process in which the perceived environment becomes transformed into cognitive representations reveals key behavioral differences among the population (Lynch 1960). The approach outlined in this chapter encodes agent representations within a model framework with a high level of cognitive capabilities, which are derived from measuring task completion performances across 42 participants on a variety of psychometric test. This chapter continues by arguing that the ways in which the concept of empirical validation is valued and measured in traditional approaches to science are misaligned with many agent-based modeling applications, especially when agents represent human subjects. As an alternative, the chapter suggests an ecological validation framework employing the triangulation of data from psychometric test, in-field behavioral measures, and model outputs to determine the credibility of the model in representing a range of everyday pedestrian behaviors. The results illustrate the ecological consistency of the data used to parameterize agent cognition, the reliability of the model parameterization in representing the phenomenon of individual pedestrian practices, and the ecological validity of the agent behaviors in mirroring real-world pedestrian behaviors. The chapter concludes by suggesting explicit modeling of cognitive processes in pedestrian agents provides a more realistic representation of the variability of the population within pedestrian spaces, as well as a more realistic representation of individual practices, abilities, and cognitive processes that influence pedestrian behaviors.

Chapter 4, “Agent based models in supporting pedestrian transportation planning and design,” discusses an applied modeling application to evaluate a transportation redevelopment project in Eugene, Oregon. Walkable neighborhoods and pedestrian-oriented design is often portrayed as a simple, solution-based approach to redevelopment that can address a myriad of structural and social issues in the city (Speck 2012), and scholars emphasize deeper engagements between street infrastructure and human-scale pedestrian behaviors are key to forming stronger theoretical approaches to sustainable urban planning (Kenworthy 2006). This paper advocates for the use of agent-based modeling to understand pedestrian behaviors and support planning decisions in response to increasingly necessary changes in the built urban environment and transportation system. First the role of agent-based models in pedestrian studies is outlined, illustrating the spatial and behavioral assumptions of how evacuation and wayfinding models represent the pedestrian, suggesting that representations of everyday practices need to move beyond the aggregate behaviors and reactive movement algorithms common to these models. Next, the chapter introduces a redevelopment project on South Willamette Street in Eugene, illustrating the complexities of the planning process, introducing the conceptual alternative for redeveloping the transportation infrastructure along this corridor, and highlighting variables in the official city assessment of the alternative concepts. It then details model entities, input data, and design concepts using the ODD protocol (Grimm et al. 2010).

The results of the model find two important considerations not calculated in the official assessment of South Willamette Street. First, not all variables are equal when considering the range of pedestrian practices within the redevelopment space, and the variables of community support and dimensional changes have a much more significant influence on pedestrians in the system than the variables of public safety and economic benefit. The model analysis also reveals that in the redevelopment of pedestrian spaces, design practices focusing on network connectivity, non-automobile facilities, and inclusive or evenly distributed development are essential to encourage pedestrian mobility. Finally, the paper suggest a framework for supporting transportation planning with agent-based models, detailing the strengths and weaknesses of agent-based models in public policy discussions and outlining how issues of model purpose, agent representation, and epistemological underpinnings need to be addressed prior to the design and implementation of an agent-based model.

The three chapters presented in this dissertation outline an alternative, human-centered representation of the pedestrian, providing theoretical, methodological, and practical solutions to conceptualize how soft variables such as emotion, motivation, and especially cognition influence the practices of walking. As cities continue to propose, design, and implement pedestrian-oriented design in response to widespread issues including climate uncertainty, energy dependency, and public health, the need for deeper engagements with human-centered pedestrian practice will continue to grow. Walking as a mode of transportation offers numerous benefits to both the individual and the community, but little is known about how real-world everyday pedestrian behaviors are influenced and impacted by changes to the urban transportation system. This is especially true in redevelopment approaches advocating for complete street design that is inclusive of multiple modes of transportation, including pedestrians. Inclusive street design approaches are considerably different than other types of pedestrian-oriented design, which often sanctions off pedestrian zones into outdoor commercial areas. Understanding how walking as a mode of transportation coexist in a system with other forms of transportation makes it critical to study of how a diverse group of pedestrians perceive, interact, and respond to changing transportation infrastructure. The research presented in this dissertation provides a rigorous data-driven approach and innovative model validation strategy to incorporate elements of spatial cognition into an agent-based model as a vehicle to understand the impacts of proposed transportation redevelopments on individual pedestrian behaviors. By approaching the issue of transportation redevelopment from a computational, human-centered perspective, this study offers unique insight into the relationship between material infrastructure and individual behaviors.

CHAPTER II
PEDESTRIANISM AND THE MORE-THAN-RATIONAL AGENT

Introduction

Cities are increasingly becoming data driven and understood via big-data analytics of smart infrastructure, geo-coded sensors, and social media data, prompting a number of concerns. Among issues such as technocratic governance, the brittleness of centralized smart systems, and the politics of big data (Kitchen 2014), perhaps the biggest concern is the way this urban future conceives of and represents the individual in the city. Smart city infrastructure is frequently arranged in centralized systems, in which a suite of hardware and software is implemented, maintained, and monitored by public-private partnerships, predominately with the intention to inform an economic and engineering approach to urban development (Townsend 2013). In this sense, both the city and its residents are conceived through a grid epistemology (Dixon and Jones 1998) in which systematically observed and ordered data ensures logical or rational municipal decision-making (Kitchen 2014) and geocoded data risks slipping "into metanarratives about spatial form, correlation, and causation" (Wilson, 2011, 359) in structural representations of urban spaces. Big data and smart grid technologies, as with other forms of top-down spatial analytics, grounds its subjects in reason and rationality, further reinforcing the rational agent urban identity (Dixon and Jones 1998).

The rational agent is a human representation with defined preferences and an ability to weigh all possible outcomes in order to achieve an optimal result. Born from rational choice theory, the rational agent embodies a normative representation of individual decision-making, one that maintains that individuals consistently strive to achieve maximum output with minimal input (Gregory et al. 2011). The persistence of the rational agent is subject to a number of critiques (see e.g.; Veblin 1988; Levi and Cook 1990; Barnes and Sheppard 1992; McLennan 1998); Veblin (1988), for example, describes human agency as more than the simple negotiation of pain and pleasure, instead framing decision-making as “a cumulative process of adaptation of means to ends that cumulatively change as the process goes on, both the agent and his environment being at any point the outcome of the last process” (390-391). While such critiques provide insight into the myriad of different contextual and more-than-rational processes that embody any given individual state, the rational agent prevails as a formal representation due to its consistency and transitivity. As a result, much of the practical and policy-oriented urban and transportation planning literature continues to frame the individual as a rational agent, one who gathers information from the environment in order to make impromptu efficient decisions according to consistent and known preferences (i.e. economy of movement behaviors and optimal routing through the gridded network). Cascetta et al. (2015) pinpoints the confusion between social and technocratic approaches in transportation discourses as reason for the permanence of the rational agent, stating:

> Transportation systems are complex sociotechnical systems and this dual nature is reflected in the literature dealing with their planning. On the one hand, the social sciences literature makes it clear that most decisions related to transportation are “wicked”, i.e. they cannot be tackled with traditional engineering approaches since they are poorly defined. On the other, transportation systems have a strong technical component affecting most of such decisions, as they have to (or should) comply with compelling technical and economic requirements. The literature on transport engineering and economics deals with transportation planning mostly as a rational process based on the formulation and comparison of alternative options (27).

Pedestrian movement is especially susceptible to this confusion. Many scholars have illustrated how pedestrian decision-making and behaviors vary dramatically in both spatiotemporal scale and social characteristics from other forms of transportation (see e.g.

Lynch 1960; Jacobs 1961; Whyte 1988; Solnit 2000) and are not easily characterized by technical and economic requirements. In many practical planning applications, however, the pedestrian continues to be framed in terms similar to the private automobile, one that makes optimal decisions based on available information and works to maximize efficiency within the gridded network. This framing ultimately renders the pedestrian as wholly structured by the material environment, lacking any form of social agency or individually human characteristics.

This paper explores alternative frameworks for representing pedestrian movement, offering both theoretical and empirical evidence to support a more-than-rational representation that is needed for slower and more human-centered understandings of everyday pedestrian behaviors, especially in light of technological trends favoring data-driven generalizability. The paper begins by examining and critiquing the roots of rational choice theory in order to understand the construction of the *homo economicus* social model. It then discusses how a particular set of human-object relationships works to spatialize the rational agent in the structural models of transportation discourses. Next, the paper details ontological differences between structural and behavioral transportation models, using empirical evidence to make space for a more-than-rational agent in formal pedestrian representations. The paper concludes with a detailed comparison of conceived, perceived, and lived spaces of the rational and the more-than-rational agent in the transportation system, providing insight into how to push pedestrian representations past the confines of the rational transportation unit towards a dynamic more-than-rational individual.

Rational Choice Theory

Rational choice theory is a utilitarian approach to human decision-making processes, based on assumptions that individuals will choose the best action within a given set of known choices to maximize net benefit. The rational agent is assumed to take into account the probabilities of all events, the potential costs and benefits of each option, and act predictably in self-interest (Gregory 2011). A rational agent "selects an action that is expected to maximize its performance measure, given the evidence provided by the percept sequence and whatever built-in knowledge the agent has" (Russell and Norvig 2010: 37). Harvey (1974) traces the rational agent to the logical empiricism of neoclassical economics, arguing the theory of effective demand produces a set of spatial interactions where individuals constantly engage in a type of cost-benefit analysis to achieve some form of capital or material equilibrium. The goal-oriented and utilitarian rational agent consistently makes decisions that, within the boundaries of a culturally specific *homo economicus* perspective, favor the highest reward at the lowest cost (Esser 1993). Levi and Cook (1990) detail the theoretical limitations of rational choice theory, stating:

> Particularly in its 'public choice' form, rational choice theory was, for a long time, no more than an extension of neoclassical economic theory applied to political institutions and behavior. We find ourselves sharing an increasingly widespread concern that the rationality attributed to *homo economicus* is too simplistic or else simply wrong when applied to actors in many political and social situations (2).

The rational agent is built on assumptions that individuals always act in self-interest to maximize preference or pleasure, and that access to information is complete and knowable (Tversky and Kahneman 1989). Additionally, in system-based analysis, there is an assumption that the aggregate behaviors of systems reflect the sum of individual rational choices. Barnes and Sheppard (1992) refute these assumptions, illustrating how the agency and situated knowledge of each individual results in unexpected difficulties interpreting and evaluating decision-making logics, and fragments the generalizability to the individual behavior. Hindess (1988) argues the multitudes of individual identities in a system favor relativistic, rather than rational representations that are fluid across different social and geographic context. Geographers have been especially critical of the rational agent representation, arguing the tradition does "not apply to the behavior of individuals once the abstract of the isolated actor is abandoned in favor of situating individuals within social relations as constituted through space and place" (Barnes and Sheppard 1992:17). Regardless of these concerns, the rational agent remains a dominant representation in the pursuit of generalizable knowledge about human decision-making behaviors in many academic and practical applications.

Rational choice theory is extended into the transportation system with concepts of network optimization, least-cost paths, and friction surfaces algorithms that characterize movement within the system with space/time utility:

> Rational choice theory postulates that all forms of spatial interaction result from a shared process of rational assessments and decision-making based on a cost / benefit analysis of the available options. Thus, according to the theory, all decisions related to spatial mobility –for example, choice of travel routes, mode of transport, destination choice –are the result of rational decisions made in order to optimize the chances of achieving set goals (Ellfers et al. 2008: 86).

Mahmassani and Chang (1987) critique the rational choice paradigm in transportation planning by acknowledging agents have limited abilities in predicting unexpected variances, such as traffic conditions, weather, and road-closures, in a classical rational decision-making model, suggesting instead that planners use models of bounded rationality that seek acceptable rather than optimal solutions through the transportation network based on some combination of previous experiences and judgment heuristics.

Simon (1991) proposes an alternative to objective rationality, suggesting a model of bounded rationality in which decision-making processes are somewhat limited by the availability of information, the cognitive limitations of agents, and real-world time-constraints. Hage (2007) maintains that bounded rationality

> (d)oes not oppose the suggestion that humans try to make rational choices in their behavior, but that the rationality is bounded. There are limits to their ability to be rational. Boundedly rational agents experience limits in formulating and solving complex problems and in processing (receiving, storing, retrieving, transmitting) information (106).

Practical applications using a model of bounded rationality often favor limitations in information acquisition, and agents typically make the most rational decision based on a fragmented dataset rather than on non-rational desires, affinities, or social motivations. Yet bounded rationality still assumes rational behavior as normative, and anything more-than-rational as marginal: "People may limit their choice to only two or three alternatives, but this is a rational process, given that they estimate the transaction costs of further analysis as too high and the benefits as too uncertain"(Gifford and Checherita 2007:3). Gigerenzer and Goldstein (1996) suggest people are bounded by time constraints and the inability to obtain global knowledge, and instead use perceptual clues embedded in the environment to build the level of insight needed to make the most rational decision. In transportation discourses, and especially in small-scale human movement and pedestrian studies, these embedded clues are known as environmental affordances, and are predicated on a relatively narrow set of human-object relations that are critical in the spatialization of rational agents (Kuhn 2002; Raubal and Worboys 1999)

Affordances and Human-Object Relations

Environmental affordances, rooted in the discipline of environmental psychology and design science, refers to the property of an object or environmental feature that, through perceptual variables, affords an individual the ability to acquire the information needed to perform an action or movement (Portugali 1996). Norman (1988) describes affordances as objective relationships between objects and people, stating: "(A)n affordance is a relationship between the properties of an object and the capabilities of the agent that determine just how the object could possibly be used" (11). While a handle on a teapot, for example, may afford a relatively straightforward relationship with an individual, affordances are often scaled up to environmental features at landscape and urban scales. Gibson (1979) defines environmental affordances as action possibilities embedded in the environment: "(A)n important fact about the affordances of the environment is that they are in a sense objective, real, and physical, unlike values and meanings, which are often supposed to be subjective, phenomenal, and mental" (121). Affordances are decidedly hard elements in this perspective, fixed and immutable. Hadavi et al. (2015) argues more subjective constructs such as beauty and aesthetics afford particular responses, similar to the ways material objects such as benches or anti-homeless spikes (Figure 1) facilitate or dissuade certain human uses, stating all aspects of human-environmental relations "reflect an assessment of the environment in terms of its compatibility with human needs and purposes, which affects effective human functioning in the settings"(20).

Figure 1 – Benches and homeless spikes are examples of material design to afford a desired human use. Photo of bench by Author. Photo of homeless spikes from Guy Corbishley (Borromeo 2015).

While the theory of affordances can be useful in drawing insight into human-object relationships, especially for the purposes of industrial design, there are serious limitations in extending this framework to human actors in a geographic context. Often when the theory of affordances is extended to transportation studies, the physical environment transforms from a place of experiences to an objective source of information, and spatial behaviors tend to be conceptualized and measured in configurational rather than human-centered terms. In this sense, our relationship with environmental objects in the transportation system is reducible to space/time efficiency metrics, neglecting potentially more meaningful relations that transcend fixed interrelations. Harman (2011) questions extent to which human-object relations can even be known, stating:

> If we define an object through its role in a system of interrelations, objects are thereby undermined, reduced to the caricatured image they present to all other things. The only way to do justice to objects is to consider that their reality is free of all relation, deeper than all reciprocity. The object is a dark crystal veiled in a private vacuum: irreducible to it's own pieces and equally irreducible to its outward relations with other things (47).

The positioning of objects as sources of objective information renders the environment a reservoir of knowledge and discredits both the individual decision makers and the objects themselves. This framing of human-object relations characterizes environmental objects as fixed in space and singular in meaning, serving as nothing more than the means to pass information and afford particular uses. This framing additionally serves to define human agency in the environment through a series static interactions and relationships rather than by their own internal capabilities, emotions, and motivations.

The representation of the rational agent, deriving knowledge from an environmental reservoir through discrete affordances, artificially segments continuous elements of space and time in pedestrian movement. Heft (2013) argues space is not structured with merely static objects, calling attention to the "temporal character arising from the perceptual flow of environmental structure that accompanies the individual movement through some expanse" (271). As an individual moves through space, prominent changes occur both within the previously perceived space and in the revealing of new spaces, creating a cognitive picture extending beyond discrete interactions (Lynch 1960; Montello 1998). Continuous views of space, however, remain at odds with modernist planning practices and, in particular, in contemporary transportation planning.

Conflicting Spatial Ontologies

Urban and transportation planning discourses typically represent human-environmental interactions with either structural configurational models or human-centered behavioral models. Golledge and Garling (2001) detail the differences between the structural and the behavior models:

> Structural models are built on assumptions such as utility maximization, complete knowledge, optimality, and lack of individual differences among the population.

> Behavioral models have been built on assumptions of satisfying principals, non-optimal behavior, constrained utility maximizations, and individual differences across the population. The structural models usually represent the aggregate movement activities of populations, while the behavioral models are disaggregated representations of the behaviors of individual or households (1).

In both types of models, underlying assumptions about the nature of space drive opposing theoretical assumptions and practical implications.

Assumptions about properties of space, most notably in conceptions of organization, measurement, connectivity, and access are key to understanding how the two approaches in planning diverge. Pulling apart assumptions about space within each approach highlights disconnects between structural and behavioral models and frames a new approach to understand the pedestrian agent.

Table 1: Spatial ontology of structural and behavioral models, highlighting key differences in how space is organized, measured, and perceived.

Class	**Structural Model**	**Behavioral Model**
Organization	Discrete	Continuous
Measurement	Euclidean	Topological
Connectivity	Symmetrical	Fragmented
Access	Complete	Uneven

Organization refers to how each approach delineates the size or extent of the space in analysis. A structural approach, with an overarching emphasis on how environmental variables influence and afford rational human behaviors, tend to conceptualize space as a hierarchal taxonomy based on categories and nested groupings (Tversky and Hemenway 1983). Beginning at broad parent categories, such as indoor or outdoor space, specific spatial classifications are products of subdivisions based on attributes. For example, outdoor space is divided into natural and built, natural spaces divided into land cover and water cover, and so on, until a predefined level of analysis is achieved. In this manner, space is reducible to smaller extents and, though each classification is a derivative of a higher class, each derivative is viewed as separate or independent of a larger system. This organization of space supports the framing of environmental objects as affordances and human action as the consequence of discrete, objective interactions.

Organizing space as a hierarchal taxonomy produces configurational spaces filled with discrete objects that can be measured and known with Euclidean and Cartesian descriptors (Franz and Wiener 2008). Euclidean-based metrics often result in a "research paradigm focusing on environmental appraisals based on the goal-fulfilling potential of the environment" (Williams and Paterson 1996: 511) and is evident across the spectrum of structural models investigating questions ranging from navigation strategy to emotional resonance in metric terms (Münzer et al. 2012; Mou et al. 2013; Wang et al. 2016). Metric measurements often lead to conceptualizations of the environment as symmetrical with object-based affordances—reference points, global alignments, and undistorted rotations (Tversky 1993)—denoting spatial structures and environmental knowledge to a rational actor. In this sense, space is complete or whole within a set of geometric parameters.

A behavioral approach organizes space not within discrete categories, but rather as the continuous and often overlapping human perception of the environment at different scales (Montello 1993). Lynch (1960) first suggested that the identity, structure, and meaning of the environment is best understood from trans-scalar perceptions and cannot be known from the summation of individual discrete objects: "In contrast to objects, environments surround, enfold, and engulf – people and objects cannot be outside or apart from their environment" (Freundschuh and Egenhofer 1997: 364). Montello (1993) reiterates the importance of continuous representations, asserting that parts of the environment can be individually perceived but cannot be separated from the whole in a rigid taxonomy. Rather, space is best distinguished through four overlapping perspectives based on projective size in relation to the human body: figural space (smaller than the body), vista space (within vision from a single vantage point), environmental space (within vision with movement), and geographic space (top-down representations). With a continuous conceptualization of space, an individual cognitive picture can include and exclude both real and imaginary relations to objects across various scales. The organization of space as continuous in behavioral models allows for an analysis of the relationships between human behavior and the environment in ways move beyond the objective-driven approaches of structural models

Environmental objects in a continuous organization of space exist in a nested topology, both independent and as part of a whole, and are best understood with non-Euclidean metrics. Egenhofer and Mark (1995: 4) argue that the nested topologies of space, what they term 'naïve geography', calls for qualitative reasoning that enables individuals to deal with partial information, multiple representations, and overlapping magnitudes of environmental objects in an "instinctive and spontaneous" manner. Lynch (1960) argues cognitive errors are predominately metrical, and rarely about the topological structure of the environment: "In geographic space, topology is considered to be first-class information, whereas metric properties, such as distance and shapes, are used as refinements that are frequently less exactly captured" (Egenhofer and Mark 1995: 9).

The theory of affordances and the configurational spaces inherent to the structural models of modern planning practices often neglect the topological connections and fragmentations of spatial objects in an environment (Hillier and Hanson 1984) that produces asymmetrical and uneven spaces not captured with Euclidean arguments (Montello 2007). A naïve geographic framework—naïve in the sense geographic space is known innately as a function of scale, context, and topology—allows for individuals to know space in ways that are dynamic, complex, and wholly more-than-rational. Empirical evidence supports the concept of naïve geographies, as illustrated by the following example.

In July 2015, 42 participants were given a route-planning test, which asked individuals to provide written instructions to navigate from an origin to a destination as if they were giving them to someone without use of the map (**Figure 2**).

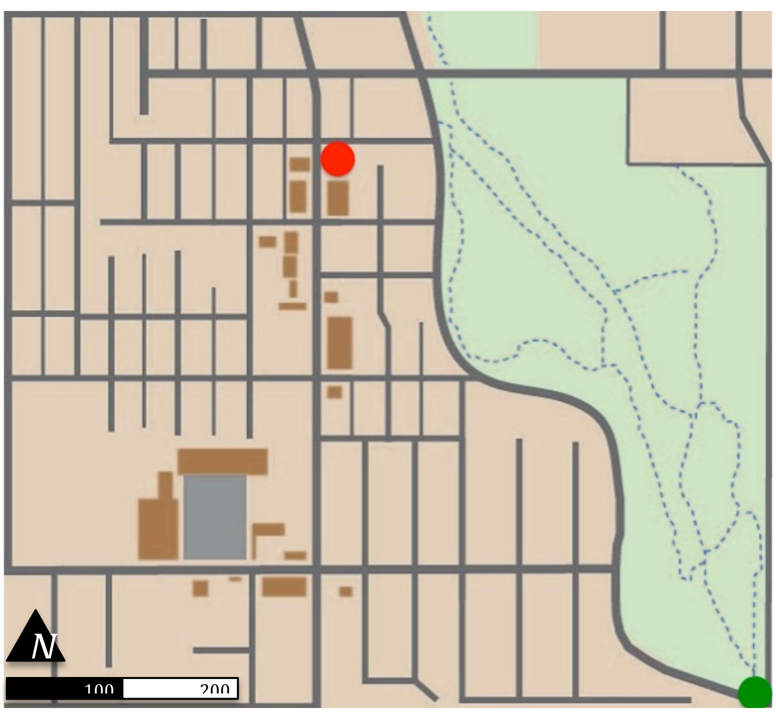


Figure 2 – Map used in route-planning test of spatial language use.

The use of spatial language in route-planning directions indicates the strategy each individual takes to translate a complex environment into a legible cognitive representation (Taylor and Brunyé 2013). The use of specific spatial discourses indicates whether an individual favors a top-down allocentric perspective or a first person egocentric perspective (Levinson 1996) when translating and communicating environmental spaces. The route instructions provided by each participant are coded according to spatial language usage, with a particular focus on the instances when individuals used cardinal directions and Euclidean distances, indicating conceptualizations of space reflected in structural models, or relative first-person directions and topological distances, indicating conceptualizations of space reflected in behavioral models[1].

In general, participants preferred human-centric or continuous representations of space to structural or discrete representations. **Figure 3** shows the average number of language uses in each category across all participants. The data indicates people favor spatial representations more closely aligned with the ontology of behavioral models, where space is conceived of in continuous, topological, and human-centered terms. The majority of pedestrian-oriented planning practices, however, favor spatial representations more attuned to the structural approaches where discrete, geometric environments produce behaviors can be known and objectively measured. While this perspective can be attributed to municipal needs to understand optimal and generalizable uses of space in the urban transportation system and particularly in auto-centric planning practices, the

[1] Cardinal directions included using terms such as north, south, east, and west. Euclidean distances included numerical values followed by a unit of measurement, 500 feet for example. First person directions include using terms relative to the human body, such as turn left or turn right. Topological distances include relational descriptions of features such as after, continuing, and following.

reductive and configurational spatial ontologies of configurational models reinforce, and leave little room for alternatives, the framing of individual pedestrians of rational agents.

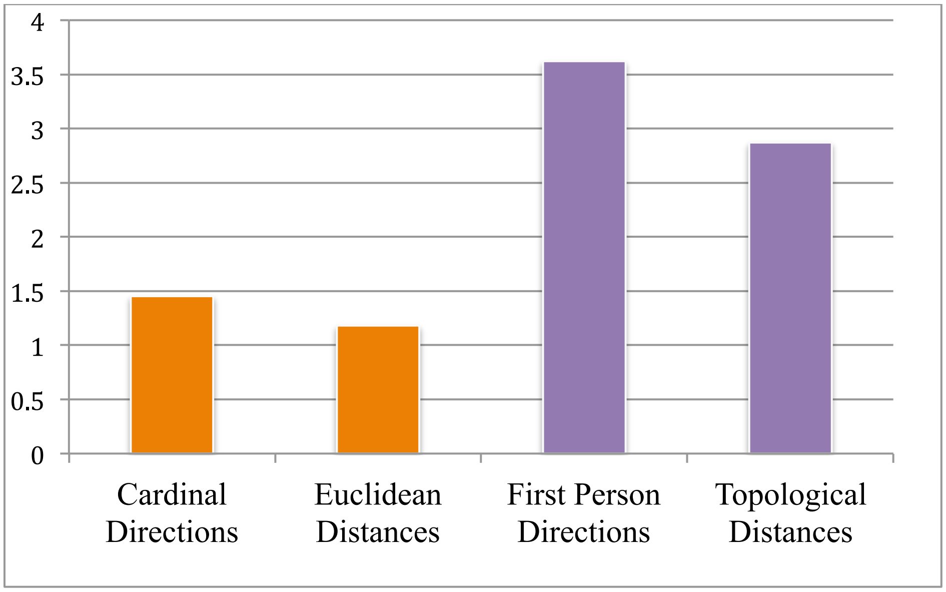


Figure 3 – Language use from participants in route-planning test. The data indicates participants use first person directions and topological distances in spatial representations over 70% of the time, compared to the use of cardinal directions and Euclidean distances.

The More-than-Rational Pedestrian Agent

Whereas the rational agent representation is deeply rooted in structural models and configurational spaces, we are left to question how we conceptualize the subject in more human-centric behavioral models, and how this subject can be incorporated into dominant planning discourses and a larger framing of the pedestrian in transportation systems. Increasingly, transportation design and planning is the domain of engineers, technocrats, and analysts with training and methods specifically tailored to the study and reproduction of configurational spaces, with little theoretical or practical tools for alternative representations. The engineering dominated technocratic perspective maintains there is “the lack of an urban theory that could link physical aspects of the urban system with its functional, social and behavioral aspects, directly and seamlessly.

This theoretical shortfall creates a gap between the analysis of things and how their manipulation in design could impact people" (Maier et al. 2009: 394).

This underlying assumption has a significant influence on the language, political processes, financing, and public perception of redevelopment projects. This influence has perhaps the greatest impact on the framing of the pedestrian in redevelopment projects, as acts of walking in many ways oppose the rational subjectivities of structural models and configurational spatial ontologies. In understanding avenues for alternative subjectivities and a formal representation of more-than-rational pedestrian agents, it is critical to understand the relationship between transportation planning practices and design science epistemologies.

Transportation planning literature commonly strives to maximize encounters between the individual and ordered, designed spaces, emphasizing efficiency and aspiring towards optimal solutions. The design science movement, much like the theory of affordances, is a modernist approach asserting the configuration of the physical form produces a set of predictable human responses (Calthorpe and Fulton 2001). Design science epistemologies construct a set of coherent laws underpinning human-object relationships, allowing for a rational and systematic way to design objects, things, and places to maximize their utility. "Design science refers to an explicitly organized, rational, and wholly systematic approach to design; not just the utilization of scientific knowledge of artifacts, but design in some sense as a scientific activity itself" (Cross 2001: 53).

In the transportation system, structural approaches frame the individual as a rational agent making optimal decision within the gridded network. In planning practices centered on the private automobile, understanding network optimization is largely driven by needs to negotiate material and political constraints while trying to maintain a working system. MacDonald (2003) credits the favoring of orthodox instrumentalist-empiricism rationality over the complexities of social agency as reason for these negotiations, while Wilson (2001) claims, "instrumental rationality bases reason on what we can observe in a neutral and dispassionate manner. Furthermore, it assumes that urban and transportation systems operate in mechanistic, predictable ways – that immutable laws about travel behavior can be discovered and used for prediction"(3). Instrumental rationality prioritizes network optimization approaches and, when applied to human movement, effectively renders the pedestrian a slower, smaller version of a car.

Friedmann (1987) argues the coupling of design science epistemologies and instrumental rationality produces a rather narrow set of technocratic mediations, where transportation planners work to accommodate new political or social demands while leaving existing arrangements undisturbed. These mediations often repurpose redevelopment projects based on successes from other locations, resulting in "clean, calculating, and homogenizing" (Dryzek 1993: 214) characterizations of urban space. Lorimer (2011) suggests aspatial and prescriptive design practices (see, e.g., Tumlin 2011; Speck 2012) that transpose design practices from one location to another further reinforce urban transportation behavior as functional and best understood in relation to rational choice and economic demand. The expectations of pedestrian behavior in design space transportation systems are stronger linked with a number of normative constructions of a human agent. In addition to strong notions of rationality and capital accumulation, human agents are conceived of with singular mobilities and sociocultural preferences. Such representations illustrate the influence of design science in transportation planning in producing ordered spaces where “environmental influences play a direct role in shaping habitual, rational behavioral patterns”(Owen et al. 2004: 67).

This structural determinism of orthodox planning assumes the relationship between material spaces and cognitive representations is a bijective, or one-to-one, function. Lynch (1960) challenges this assessment, arguing the transformation of the physical environment to mental image “does not connote something fixed, limited, precise, unified, or regularly ordered (1960: 10). Lynch argues instead for the concept of imageability, or the theory that design may create cognitively legible environments, perceptual saliency, and in some cases consensus among the population. Raban (1974) extends the idea of subjective representations, calling attention to the mismatch between the hard and soft elements of the city to illustrate how individual negotiations between material environments and cognitive representations produce a fluid and shifting urban subject, disrupting many of the assumptions about rational agents and immutable materiality:

> The city goes soft. It awaits the imprint of an identity. For better or worse, it invites you to remake it, to consolidate it into a shape you can live in. You, too. Decide who you are, and the city will again assume a fixed form around you. Decide what it is, and your own identity will be revealed (11).

Raban views the urban environment not as fixed or immutable as in the world of orthodox or technocratic planning, but as topological spaces defined by relations between individuals and objects undergoing continuous shifts as hard material contour around instinctive, spontaneous, and fragmented human representations. Raban and Lynch both provide an alternative set of mediations to the theory of affordances in theorizing about the daily negotiations between individuals and designed spaces.

Perhaps it is in these everyday negotiations that we can begin to construct alternative subjectivities, representations of individuals in the transportation system not bounded with only rational behaviors. The more-than-rational agent sometimes makes rational or optimal decisions in concert with the designed spaces; occasionally a decision is rational or optimal despite design, as is the case with informal desire paths[2]. In other instances, the more-than-rational agents' actions are tied to personal experiences and cognitive representations, emotional or instinctive responses, and subversive or performative acts.

Lefebvre (1991) provides a fitting framework within which to conceptualize the relationship between physical and social spaces, proposing the spatial triad to define differences between representations of space, representational space, and spatial practice. Briefly, representations of space are viewed as conceived spaces or the discourse on space and include maps, plans, designs, and other predominately planning instruments. Spatial practice is viewed as the perceived space, including the ideas, perception, and imagination of the subject. Representational space is viewed as the lived spaces or the discourse of space, and includes what might be considered daily routines and lived experiences. This framework has been instrumental in the works of many urban geographers illustrating how the representations of space in orthodox planning practice actually produces multiple representational spaces and spatial practices (Wunderlich 2008; Ehrenfeucht and Loukaitou-Sideris 2010; Edensor 2010; Middleton 2011).

Specifically, Middleton (2011) provides a detailed analysis of the relationship between pedestrian practices and sidewalk infrastructure, illustrating how representations

[2] See the podcast 99% Invisible (01/25/16) "Least resistance: how desire paths can lead to better design" for a detailed account of emergent design and informal pedestrian practices.

of spaces assumed to structure pedestrian movement actually produce far more than normative responses and expected behaviors, contending the study of these discrepancies allows for deeper engagements with the situated knowledge and embodied practices of people in designed urban spaces, echoing DeBord's (1955) assertion that the best way to know the city is through the emotions and habitual behaviors of individuals. Middleton's focus on the emotions, experiences, and events embodied by the pedestrian in the spaces between the origin and destination gives agency to individuals that are otherwise rendered "inert and lifeless" (Bissell 2010: 271) by the overriding focus on technocratic design and material conditions. The framing of walking as performative illustrates the multiple ways of reading/knowing design, drawing out alternative couplings of perceived and lived spaces and highlighting the permeability of orthodox representations of spaces. In contrast to the structural models of urban planning where designed space produces configurational meanings and expected, rational behaviors, performative pedestrianism suggest designed space also produces subversive and instinctive practices in order to reclaim, repurpose, or remodel the space to the soft images of the individual.

The practice of walking itself, in contrast to other forms of movement, has long been situated within discourses of resistance to established planning practices. Jacobs (1961) stresses there is much more to streets than corridors for movement between two discrete places, stating: "downgrading and minimizing their social and their economic part in city life is the most mischievous and destructive idea in orthodox city planning" (88). Whyte (1989) echoes this claim, using a variety of visual and auditory methods to show how human-centered practices drive the social life of the city and reclaim urban spaces from dominant or prescribed uses. De Certeau (1984) rejects that pedestrian behaviors are shaped by material form, arguing instead that walking can be a tactic of democratic resistance to disrupt the spaces produced by rational planning. He describes this relationship by stating:

> If it is true that a spatial order organizes an ensemble of possibilities (e.g. by a place in which one can move) and interdictions (e.g. by a wall that prevents one from going further), then the walker actualizes some of these possibilities. In that way, he makes them exist as well as emerge. But he also moves them and invents others, since the crossing, drifting away, or improvisation of walking privilege, transform, or abandon spatial element (98).

More-than-rational pedestrian behaviors can then act to disrupt many of the analytical assumptions about how people perceive and behave is space, and walking can becomes one of the primary ways citizens can practice resistance to the institutional power inscribed in the landscape through modernist planning practices (Hubbard 2006). As Harvey (1974) details, the rational agent traces back to neoclassical theory and the assumptions of maximum accumulation and lowest cost embedded within the *homo economicus* social model, resulting in a set of predictable goal-oriented and utilitarian behaviors. Whereas the rational agent representation ignores performative or experiential practices of walking, the more-than-rational agent representation openly and explicitly embraces the full range of more-than-rational, less-than-capital pedestrian behaviors.

Framework for the More-than-Rational Pedestrian Agent

This paper proposes a new framework to understand the urban pedestrian, drawing on Lefebvre's (1991) spatial triad to frame both the rational and the more-than-rational agent (**Table 2**).

Table 2 - Framework for the more-than-rational agent details key distinctions between the rational agent and the more than rational agent in different categories.

	The Rational Agent	**The More-than-Rational Agent**
Spatial Ontology	Configurational	Topological
Representations of Space	Design Science	Human Centered
Representational Space	Utilitarian	Performative
Spatial Practices	Affordances	Imageability
Materiality	Hard	Soft

Highlighting key distinctions between a rational and a more-than-rational pedestrian representation, the framework specifically focuses on key differences in Lefevbre's (1991) spatial triad as well as in urban materiality and ontologies of space. It shifts the focus from the material to the immaterial (Latham and McCormack 2004) and contributes to the reconciliation between the cognitive and the concrete in understanding the sociospatial urban process (Dear and Flusty 2010). Increased engagements with the experimental and human dimensions of walking contributes to the field of planning by expanding the conversation to include frameworks of performance, emotion, and more-than-rational behaviors while simultaneously illustrating flaws in the emphasis on design science, rational subjectivities, and the idea of maximizing encounters underlying much of the transportation planning discourse. Such reconciliations work to conceptualize alternative forms of agency and behavior in pedestrian subjectivities, shedding light on the multitude of human perceptions and embodied practices in conceived spaces and illustrating how design enables both optimal rational behaviors as well as a multitude of subversive engagements actively working to reclaim the design for other purposes.

As transportation discourse and redevelopment policies becomes increasingly driven by geospatial and gridded data points, there is an urgent need to develop new approaches to measure and know the salient dimensions of human-environment interactions on terms more closely reflective of actual human experiences. The more-than-rational agent framework provides a human-centered component to the planner's toolkit, allowing for an alternative human representation in urban transportation modeling systems, including forecasting, agent-based, and criteria-based assessment models. Incorporating a human-centered representation of the pedestrian, one that accounts for more than analytical design and intended behaviors, provides a key to deepening understanding of both the embodied practices of walking as well as the credibility of system-based assessments of pedestrian-oriented redevelopment projects.

Conclusion

Rebecca Solnit writes, "walkers are practitioners of the city, for the city is made to be walked. A city is a language, a repository of possibilities, and walking is the act of speaking that language, of selecting from those possibilities. Just as language limits what can be said, architecture limits where one can walk, but the walker invents other ways to go." (2000: 213). As we approach a future city where data points replace human experiences, it is critically important to reevaluate the rational agent representation that has come to dominate technocratic assessments and urban redevelopment processes. The rational agent is embedded with utilitarian or optimizing behaviors that rely on configurational spatial ontologies, fixed environmental affordances, and hard urban materiality. This paper illustrates how orthodox urban and transportation planning practices, including a rather narrow view of human-object relationships rooted in the theory of affordances and epistemologies of design science, produces configurational spaces in which rational pedestrians make spatiotemporal assessments to maximize efficiency. This heavily structured framing of urban transportation spaces essentially renders the pedestrian as a slower moving version of the private automobile.

In response, this paper introduces a framework for a more-than-rational agent, a formal representation allowing for pedestrian agents to perceive and behave in a manner that is not reducible to the form of the environment. The more-than-rational agent embodies emotional, cognitive, and habitual characteristics, allowing for softer human-environmental encounters and performative engagements. In contrast to the geometric or configurational spaces of the rational agent, the more-than-rational agent relies on topological assessments of the environment that allow for fragmented, asymmetrical, and uneven spatial representations. A route-planning study supports this framework, providing empirical evidence that humans typically communicate spatial movement in topological rather than configurational language. Drawing on Lefebvre's spatial triad to highlight distinctions between the rational and more-than-rational agents, this paper illustrates the opposing positions of design science and human-centered in conceived spaces, affordances and imageability in perceived spaces, utilitarian and performative practices in lived spaces. The more-than rational agent framework serves as an alternative formal representation for increasingly data-driven and gridded urban analytics, giving agency and life to pedestrians typically viewed as inert, mechanistic, and predictably rational. Expanding representations of the human pedestrian to a more-than-rational agent enables deeper and more meaningful engagements with how people move through and experience urban spaces.

The next chapter in this dissertation takes the theoretical more-than-rational framing of the pedestrian proposed in this article to create a formal agent-based model.

This model explicitly injects agents with cognitive capabilities as measured by a set of psychometric test. In doing so, the following chapter discusses the role of model validation in representing human subjects, proposing a method of ecological validation to evaluate the credibility of the model. Additionally, the next chapter builds on the theoretical framework proposed in this chapter by illustrating how the modeling the cognitive capabilities of agents reveals the range of individual differences in human subjectivities and the limitations of the rational agent representation.

CHAPTER III
ECOLOGICAL VALIDITY OF HUMAN REPRESENTATIONS IN AGENT-BASED MODELS

Introduction

Deepening understandings of pedestrian movement is important in many fields of study, including geography, urban design, architecture, and transportation planning. In recent years, agent-based simulation models have become an increasingly common approach to understanding various aspects of human movement (Torrens 2012). Computational agent-based models of pedestrian behaviors allow for an iterative and systematic investigation of movement scenarios, ranging from evacuation events to everyday pedestrian activities, many of which may be difficult to observe in real-world empirical studies. In the majority of agent-based models, "heterogeneous and autonomous individuals share a common environment and act upon it, while simultaneously interacting among each other in a quest for realization of some self-interest or common-interest" (Ligmann-Zielinska and Jankowski 2007: 317).

Agent heterogeneity implies agents within the model environment are at least capable of moving beyond the often simplistic and generalizable representations inherent to conventional empirical models (O'Sullivan and Perry 2013), allowing for a myriad of emotional, social, and wholly more-than-rational behaviors to be embedded in the representation of individual humans, including subversive or non-goal oriented motivations, personalized cognitive maps of the environment, and decision-making heuristics based on incomplete or socially constructed information (Waddell 2002). Cognitive variables are of particular importance, as the process in which the perceived external environment becomes transformed into internal representations or cognitive maps reveals key behavioral differences among subjects (Lynch 1960). Golledge and Garling (2001) highlight the importance of studying individual differences in cognitive processes, stating:

> Cognitive maps, thus, are the conceptual manifestation of place-based experiences and reasoning that allow one to determine where one is at any moment and what place-related objects occur in that vicinity or surrounding spaces. As such, the cognitive map provides knowledge that allows one to solve problems of how to get from one place to another, or how to communicate knowledge about places to others without the need for supplementary guidance such as might be provided by sketches or cartographic maps (6).

Indeed, cognitive maps are incredibly powerful and individualized representations of how people obtain, store, and use spatial information for both movement and communication. Agent-based models possess a unique ability to account for such individual differences through a parameterization of heterogeneous human representations in the model environment. Despite these capabilities, many agent-based pedestrian models scale up isolated entities to represent the whole community (Axtell 2003). As this paper will argue, homogenous representations persist in large part due to a model validation processes rooted in statistical and predictive modeling conventions.

There is much debate in the field of agent-based modeling about how to best validate whether or not a particular model represents a phenomenon, with suggestions ranging from confrontational statistics with observed real-world data to inductive reasoning through exploratory simulations (Sargent 2005). At the core, however, there is an epistemological mismatch between the validation techniques of deductive sciences and the process-oriented approaches of computational simulations designed to investigate nondeterministic or emergent outcomes (Thrift 1999). As Manson and O’Sullivan (2006) explain:

> Linking pattern to process is an important aspect of model validation. The difficulties of validating complex spatial models are manifold, and include the spatiotemporal nature of complex models of space and place and the amount of data produced. Expressly complexity based models also carry with them the expectation that they should exhibit behavior such as emergence, sensitivity to initial conditions, and self-organized criticality. These behaviors are at odds with many standard methods, requiring the construction of new validation tools (686).

A possible solution to this mismatch is to turn attention away from experimental and external validation techniques and instead focus on the ecological validation of model entities. In models with pedestrian entities, the need to validate with deductive techniques often drives a specific type of model design and limits the range of possible outputs or types of knowledge production; many existing pedestrian models use some combination of reactive physical and rational behavior heuristics to drive movement, often producing an analysis of coarse-grained patterns and generalizable knowledge that can be externally validated against some set of real-world observations. A rational behavior model, for example, illustrates how the majority of pedestrian agents take an optimal or structurally preferential route between two places, which can be easily validated with either traffic monitoring sensor data or space syntax analysis. This hypothetical model, however, can say little about why variations from optimal routing behaviors exist, and more importantly, what individual factors drive the observable differences in behaviors.

In order to capture a more complete representation of everyday pedestrian movements, this paper proposes blending a behavioral approach to model design with an ecological validation protocol specifically targeting individual difference in spatial cognition in agent representation. It begins by discussing the concepts of ecological validity, detailing how it differs from experimental and external validation processes. The paper then details an innovative experimental design, defining a set of cognitive variables and set of associated psychometric methods for collecting data about human spatial processes and parameterizing cognitive representations in computational agents. The paper concludes by discussing the results of the ecological validation method using a triangulation of psychometric testing data, field observations, and model outputs, suggesting a similar protocol for future research studying everyday pedestrian behaviors.

Behavioral Models and Ecological Validation

Many existing pedestrian models employ an objective-oriented approach that gives pedestrian agents simple decision-making heuristics in order to generalize behaviors within a set of contextual constraints. The objective-oriented approach is built primarily on assumptions of agent optimality within a network, with little thought given to how individual differences in abilities, cognition, and behaviors may effect observable pedestrian behaviors (Golledge and Garling 2001). Behavioral geographers have long known that individual cognition, environmental saliency, and spatial behaviors are not homogenous across populations, varying dramatically from person to person across various social and spatial contexts (Golledge and Stimson 1997). Individual differences in human pedestrians exist both in the amount of existing knowledge about places, locations, and other components of the transportation network (Allen 1999) as well as in the individual's ability to learn such information from real-world experiences in the environment (Montello 1998). Bell (2000) extends the discussion on individual differences, suggesting place-based knowledge, environmental familiarity, and geographic scale make generalizable comparison about spatial behaviors between locations uncertain. Within subject reliability can also prove uncertain as changing motivations, trip purposes, and emotional engagements across time can make spatial movements unpredictable. Given that many behavioral geographers argue observed pedestrian activities are rarely reducible to casual external variables, why then is the objective of many agent-based pedestrian models the production of generalizable knowledge?

In simple terms, model design is often driven by the need for analytical tractability and model validation through backend mathematical and statistical operations. Golledge and Garling (2001) point to how the underlying design of utilitarian pedestrian agents in wayfinding and navigation models allow for relatively straightforward validation protocol with geospatial network analysis tools. Robin et al. (2009) illustrate how outputs from discrete-choice leader-follower pedestrian models can be validated with data collected in controlled experimental conditions. Berrou et al. (2005) uses surveillance cameras to correlate pedestrian behaviors in evacuation models with real-world data of people boarding and exiting subway platforms. These approaches successfully validate the movements of the pedestrian agents with empirical data, but each have significant limitations in relating model outputs to real-world everyday pedestrian practice and provide little insight beyond the coarsest layer of aggregate behaviors. In these cases, as is the case with many pedestrian models, design objectives and epistemologies are linked to validation methodology.

The majority of pedestrian models produce agent behaviors that can be correlated with either geospatial analysis or real-world observations, often focusing on the routes between locations rather than on what internal and individual processes are driving patterns of movement. From this standpoint, pedestrian models are designed to produce tractable results that can be validated with confrontational measures and be generalizable across spatial scales and geographic locations. A deeper look at the concept of empirical validation indicates why this is the case. In practical modeling applications, validation is the process to determine whether or not the model is a reasonably accurate representation of a phenomenon and the simulation outputs correspond with real-world observations (Kelton and Law 2000). Schlesinger et al. (1979) defines model validation as the "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (39). Often models are confrontationally validated against real-world observations, under an assumption that formal statistical methods increase the credibility of simulations models and make outputs more robust for usage in policy-oriented debates (Rykiel 1996). Barlas (1996) suggest validity should be viewed not as the matching of output data, but rather through ensuring the internal structure of the model embodies the theory of how the system works.

Diverging views about the nature of model validation reflect a divide in philosophies of science. On one hand, a traditional empiricist philosophy of science views a model as a reflection of reality, and the validation process as one to determine whether that reflection is correct or incorrect in relation to a set of observations (Barlas and Carpenter 1990). An empirical philosophy of validation **(Figure 4)** views the modeling process an abstraction of a phenomenon producing a set of results through simulations; the results are then compared to real-world observations of the same phenomenon to ensure the model is a valid representation. In this sense, model validation is a measure of accuracy.

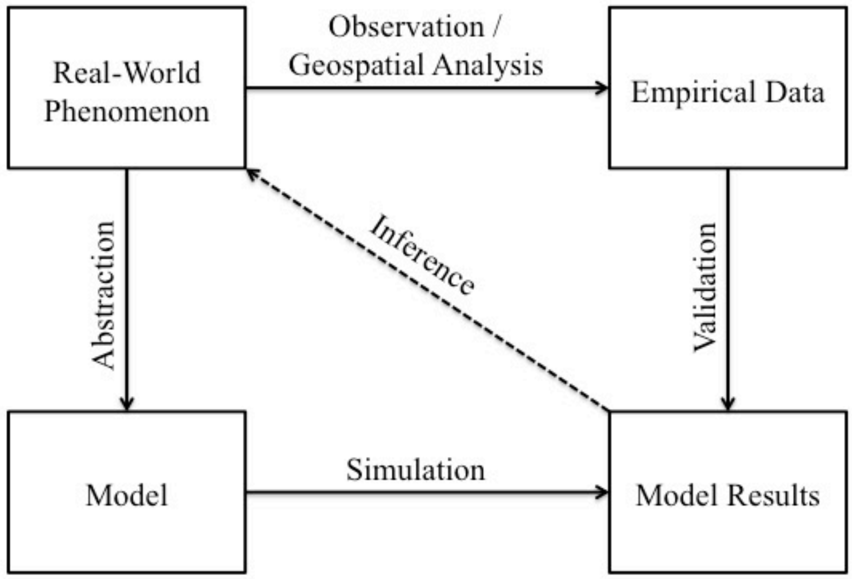


Figure 4 – Diagram of empirical philosophy of validation.

Approaching validation as a measure of accuracy can be especially problematic in both complex systems and spatially explicit models. Complex systems often exhibit behaviors that are not easily reducible to the sum of individual parts and initial conditions (Manson 2001), resulting in a theoretical misalignment between process-oriented simulations and discrete real-world observations. Oreskes et al. (1994) argues traditional concepts of external empirical validation—comparisons of model outputs with empirical observations, historical data, or null model outputs using formal statistical testing (Sargent 2005)—to establish a model as an accurate representation of reality, is impossible. Only systems that are measurable over time with constant and reliable behaviors can truly be validated with these confrontational approaches (Oreskes, 1998). Manson and O'Sullivan (2006) reiterate this concern when discussing spatially explicit models, arguing confrontational data must be both consistent over time and invariant across space in order in order to validate model representations in the traditional empirical sense. Brown et al. (2005) illustrates how stochastic elements embedded in model design and the path-dependency of spatial distributions often produce insignificant macro-level statistical correlations while illustrating realistic micro-level behaviors, demonstrating how agent-based simulations produces knowledge about spatiotemporal real-world processes regardless of misalignments or mismatches in traditional model validation results.

A more relativist or holistic view of science positions a valid model as one of the many possible ways to represent a real-world phenomenon, and one that cannot be proven to be any more or less effective than other representation in an absolute objective sense (Barlas and Carpenter 1990). In this framework, there is no clear foundation for validation procedures; rather, the approach varies based on the construction of the representation and judgment of the modeler (Feinstein and Cannon 2003). Barlas and Carpenter (1990) outline how models should be evaluated on a continuum rather than in binary terms:

> No model can claim absolute objectivity, for every model carries in it the modelers world view. Models are not true or false but lie on a continuum of usefulness. Model validation is a gradual process of confidence in the usefulness of the model; validity cannot revel itself mechanically as a result of some formal algorithm. Validation is a matter of social conversation as usefulness is a conversational matter (158).

By accepting a relativist philosophy of science that knowledge is holistic and social, both the processes of model design and validation protocols are rooted to the epistemological underpinnings of the modeler. From this perspective, it is hard to imagine many instances where representations of human agency or representations of complex systems, both common practices in the world of agent-based modeling, would align with reductionist epistemologies. Furthermore, there is often a many-to-one relationship between model processes and model outputs (O'Sullivan 2004). In other words, many different models can produce the same or similar outcomes. This issue of equifinality is not solved by confronting the model with historical data and recalibrating parameters until statistical correlations deems the model valid, rather this problem requires a reimagining of qualitative and quantitative measures that are sensitive to multiple and subjective representations.

Given these opposing views, the challenge of linking pattern and process is finding ways to express the external capabilities and limitations of the model while still maintaining a sense of internal robustness (Manson and O'Sullivan 2006). A relativist philosophy of model validation does not imply that formal quantitative validation tools be abandoned, and in may cases such approaches prove beneficial in evaluating the usefulness and credibility of a model, rather to move the concept of validation "beyond the sterility of positivist science and linear modeling"(Byrne 2005: 100). Sterman (1992) suggest reworking the notion of model validation requires an integration of contrasting philosophies of science and views of data, stating:

> Data are not only numerical data, that 'soft' (unmeasured) variables should be included in our models if they are important to the purpose. Despite the critical importance of qualitative information some modelers restrict the constructs and variables in their models to those for which numerical data are available, and include only those parameters that can be estimated statistically (523).

A greater inclusion of the difficult to measure or soft variables is essential in pedestrian modeling, especially when considering the wide breadth of pedestrian-oriented literature suggesting walking behaviors are driven in large part by cognitive, experiential, and social processes (Lynch 1960; Jacobs 1961; De Certeau 1984; Whyte 1988; Solnit 2000).

Parker et al. (2003) note that cognitive constructs range in depth in agent representations, explaining that "the term cognition ranges in applicability to situations ranging from relatively simple stimulus-responses decision making to the point where actors are proactive, take initiative, and have larger intentions" (317). Russell and Norvig (1995) argue that human representations should, at a minimum, have internal strategies to perceive and react to changes in the environment. Most models incorporate some sense of cognition with learning and memory algorithms embedded within agents, though O'Sullivan (2008) argues for deeper agent representations when he specifically advocates for greater ranges of emotional and cognitive capabilities in agent design. Many current pedestrian models are satisfied with a relatively shallow cognitive representation, instilling into agents some combination of affordance theory, physiological or perceptual variance, and value-laden model environments (Raubal 2001; Torrens 2012) as proxies for more substantial engagements with cognitive constructs. These interpretations of cognition are examples of representational design following established validation methods, as these fairly deterministic cognitive strategies can be confronted with geospatial or observational data to draw links between cognition and behavior in order to produce an aggregated pattern of people moving through space. To move from the generalizable to the individual requires engaging in a deeper sense of cognition in pedestrian models and a more intentional engagements with individual differences and cognitive abilities in a thoughtful and meaningful way.

To meet this need, this paper introduces a new behavioral approach to incorporate and validate cognition into agent representations, suggesting a deeper cognitive agent can be parameterized with data generated from psychometric test and ecologically validated with field observations of individual spatial behaviors. Rather than correlating the multi-agent pattern of behavior generated by the model against real-world observations of aggregated pedestrian practices, this approach individually parameterizes each agent with a collection of laboratory data generated about selected cognitive variables. Each laboratory test is coupled with a set of related field measure to correlate psychometric test performance with a set of observed real-world behaviors using the same cognitive task, ensuring within subject reliability and ecologically validity for each input variable. This process (**Figure 5**) moves spatial pedestrian models beyond the external validation methods commonly used to make generalizable claims across spatial scales and geographic context (Stokols and Shumaker 1981) and provides a framework to deepen cognitive representations in pedestrian agents.

Ecological validation, in environmental and social psychology literature, is the extent to which the methods, stimuli, and environment replicate or mimic real-world counterparts (Brewer 2000): "Ecological validity refers to the extent to which the environment experienced by the subjects in a scientific investigation has the properties it is supposed or assumed to have by the experimenter" (Bronfenbrenner 1977: 516). Specifically, strong ecological validity requires attention to the level of realism or representative design in laboratory-based performance tests, specifically focusing on the abstraction of essential elements to maintain perceptual, task, and response fidelity between laboratory measures and real-world activities (Araujo et al. 2007). Linking human and artificial agents requires detailed human subject data about cognitive constructs to appropriately parameterize computational representations (Duffy 2006).

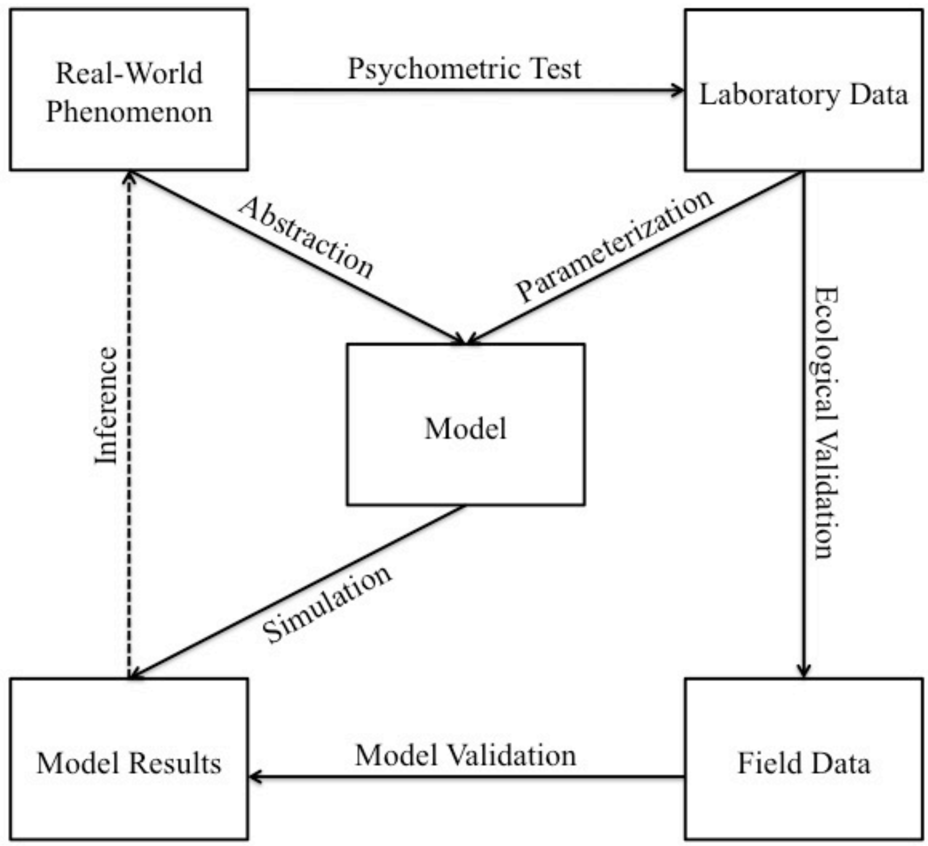


Figure 5 –Diagram of ecological validation approach to agent-based models.

If the data used to parameterize the cognitive capabilities of agents within the model environment is ecologically validated with intrasubject behavioral measures in the real-world environment, agent behaviors within the model environment can be correlated with those observed in the real-world environment to infer model validation. The interrelation between the input, output, and validation datasets through a detailed assessment of instrument reliability and ecological validity provides a level of theoretical integrity and analytical tractability to the modeling process while simultaneously achieving a deeper and more individualized sense of cognitive representation.

Cognitive Variables and Methods

Deepening agent representations of cognition and experiences during pedestrian movement necessitates the adoption of a behavioral geographic perspective in model design. Golledge and Stimson (1997) argue the observed differences in spatial behavior are best explained through the examination of individual differences in cognitive processes underlying spatial reasoning. Montello (1998) and Lobben (2007) both provide empirical work illustrating individual differences in the extent and accuracy of environmental knowledge acquisition, detailing how differential strategies for encoding environmental information influences individual spatial behaviors. Gilbert (2006) argues for the importance of incorporating cognitive architectures in social simulation, detailing how human behavior is driven by internal variables and deviates significantly from the physics-based or leader-follower behaviors commonly employed in pedestrian models. Using a behavioral geographic approach, this paper provides a clear example of how to incorporate data-driven elements of individual human cognition into the agent-based modeling framework as a way to better understand individual human movement through the environment.

The following section details the methodological framework to interject agents with an empirically driven embodied cognition architecture whereby cognitive capabilities influence the bodily experiences of agents in the model environment (Portugali 2011). First, a set of psychometric laboratory tests generates the necessary data to parameterize the cognitive variables in the agent. Each psychometric test targets a specific cognitive variable and has an associated in-field measure to evaluate the ecological reliability of the psychometric data with a comparable real-world task.

Cognitive variables are intangible constructs and thus are difficult to directly measure. Psychometric test are standard methods used to measure an individual's cognitive capabilities and preferences, strengths and weaknesses, and overall task completion strategies (Kline 1986), and are useful to investigate individual differences in environmental cognition (Allen 1999; Montello et al. 1999; Hegerty et al. 2002; Hegerty and Waller 2005). In-field measures, designed to replicate cognitive task in a real-world geographic space, are used to link the cognitive variables to spatial behaviors and to ecologically validate the psychometric test (Lobben 2007).

Table 3 – Detailing variables, psychometric test, in-field measures, and model outputs in the design of agent cognition.

Cognitive Variable	Psychometric Test	In-Field Measure	Model Output
Spatial memory	Sense of direction test	Environmental location measure	Agent knowledge of local environment
Non-metric location coding	Self-location test	Environmental location measure	Agent searching
Metric location coding	Environmental perspective test	Perspective changing measure	Agent knowledge of global environment
Path integration	Spatial engagement test	Direct path movement measure	Agent optimal routing
Spatial reference frame	Route planning test	Navigation decision measure	Navigation strategy

Initial model design relies on data generated from five psychometric tests to evaluate the environmental cognition of the participants. Each psychometric test targets a specific cognitive ability and generates the data used to parameterize cognitive variables in the agent representation. Each cognitive variable is reflected in a specific model output of agent behavior (**Table 3**). After agent parameterization, model simulations generate the data to ecologically validate the spatial behaviors of the computational agents with the real-world spatial behaviors of individual research participants.

Spatial Memory

The first psychometric test used in parameterizing agents is the Santa Barbara Sense of Direction Scale (SBSOD), which research has shown to be a reliable self-reported test measuring a participant's ability to encode and remember spatial configurations in the environment (Hegerty et al. 2002). Hund and Nazarczuk (2009), suggest individual differences in sense of direction lead to significant differences in wayfinding ability and the extent of spatial information acquisition in new environments. Data from the SBSOD serve as the independent variables in parameterizing the cognitive variable *spatial memory* in the agents. In the model, *spatial memory* is measured as the agent's ability to remember the location of objects while moving through the environment (McNamara 2002) and is recorded by the extent to which an agent has knowledge of the local environment during the simulations.

The *spatial memory* field data are generated by measuring participant knowledge of local environmental features encountered on a route through the study area (**Figure 6**). At the beginning and again at the end of the testing session, each participant is asked to identify the location of 12 environmental features, either notable built features within the study area or prominent landmarks in the city. Data are measured as the total number of features known as well as the difference before and after the field-testing session. The data generated from the environmental knowledge field measure are correlated with the SBSOD data to evaluate the reliability of the psychometric test data to parameterize the cognitive variable *spatial memory* in the agents. The model output of local environmental knowledge model is correlated with the environmental knowledge field data to evaluate the ecological validity of agent behaviors in the model.

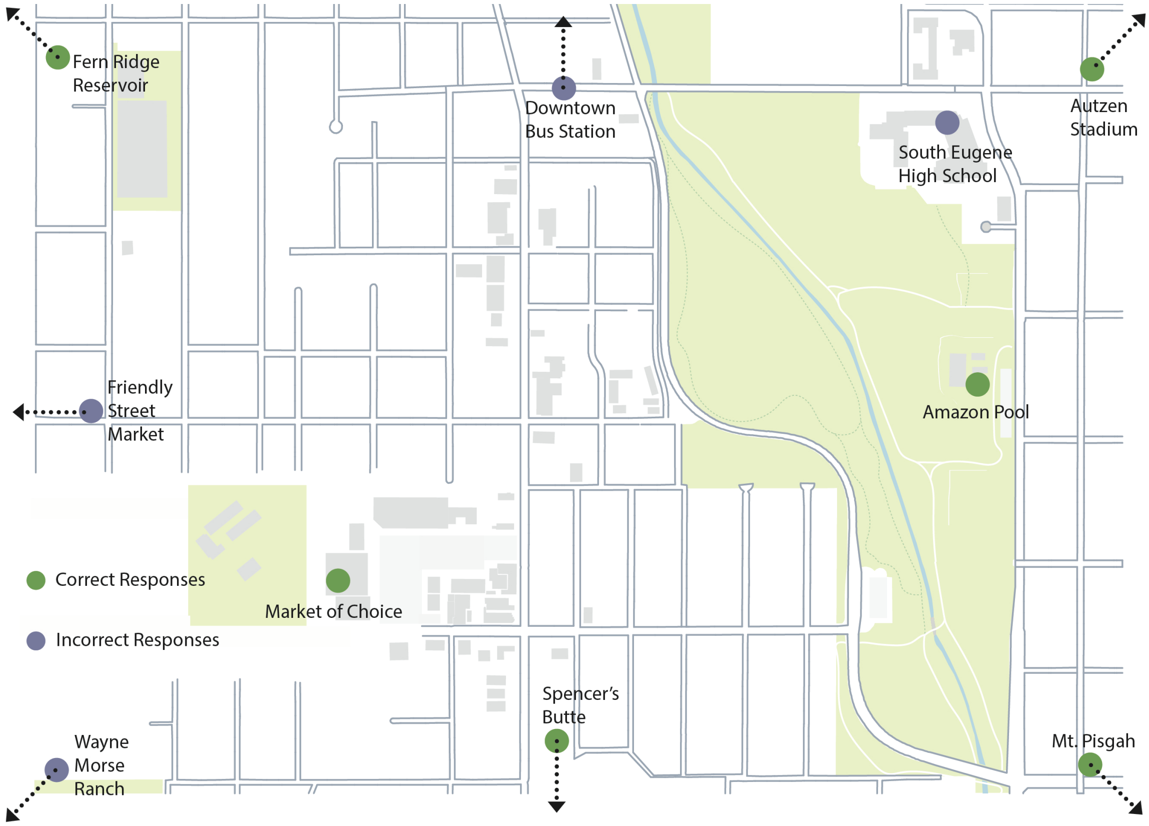


Figure 6 – Data analysis example for the environmental knowledge measure.

Non-Metric Location Coding

The second psychometric test used in parameterizing agents is a self-location test that ask participants to mark the appropriate location on a map and draw an arrow to indicate direction facing based on information in an image. The self-location test evaluates a participant's ability to use landmarks and spatial patterns to place oneself in the environment (Lobben 2004). "It is possible to encode or represent the positions of each object in relation to oneself. This type of frame of reference is referred to as egocentric and is defined by subject to object relations. The locations of objects in space are represented with respect to a personal agent" (Zaehle et al. 2007). Self-location relies on the participant's ability to define the spatial structure of the environment based on a first person reference frame, indicating non-metric conceptions of space (Burgess 2008). The data generated from the self-location test serves as the independent variables to parameterize the cognitive variable *non-metric location coding* in the agents. In the model, *non-metric location coding* is the agent's ability to use an egocentric, first person perspective to perform on-the-fly, piecemeal updating of the internal cognitive representation (Wang and Brockmole 2003) during navigation and is measured as the time of agent searching to self-locate in the model environment during the simulations.

The *non-metric location coding* field data are generated by guiding participants to five different locations in the study area and having them locate themselves on a blank map and draw an arrow indicating the direction facing. Data are measured by the locational and angular distortion between the participant's response and the correct answers (**Figure 7**). The environmental-location field task relies on the participant's ability to use environmental objects in respect to their relative position to self-locate within the study area. The data generated from the environmental-location field measure are correlated with the self-location psychometric test to evaluate the reliability of the psychometric test data to parameterize the cognitive variable *non-metric location coding* in the agents. The model output of agent search time is correlated with the environmental-location field data to evaluate the ecological validity of agent behaviors in the model.

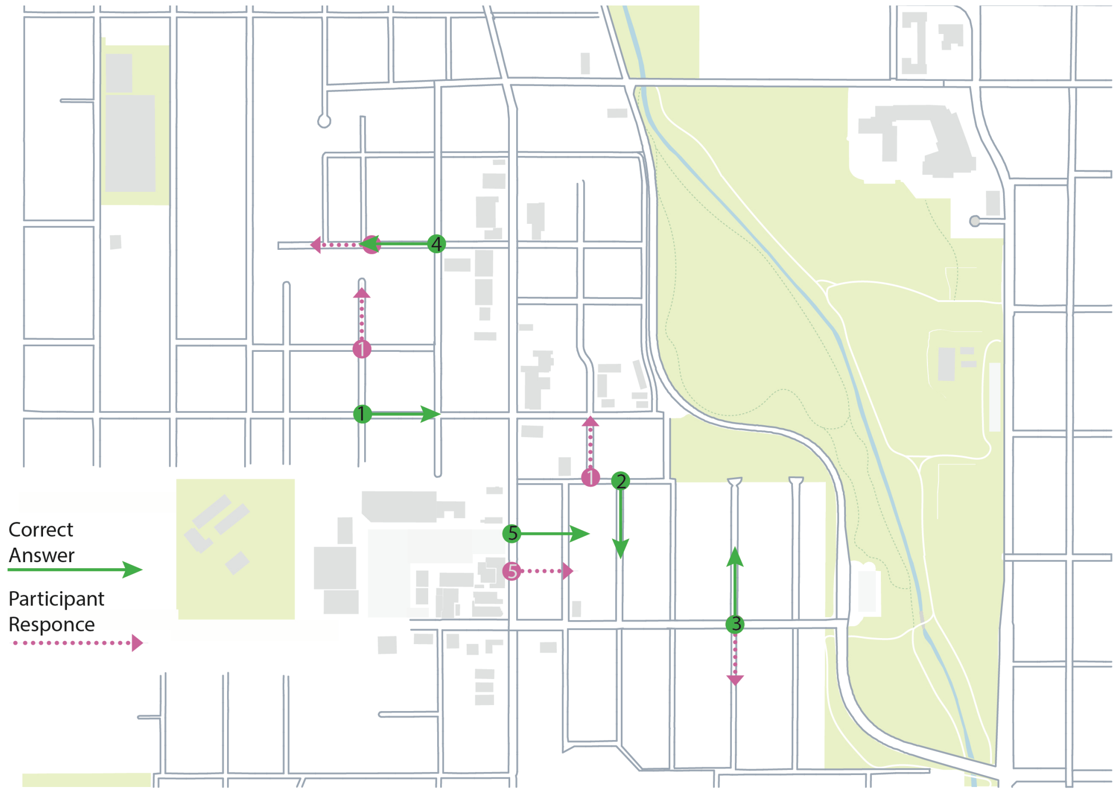


Figure 7 – Data analysis example for the environmental location measure.

Metric Location Coding

The third psychometric test used to parameterize agents is an environmental perspective test that evaluates participants' abilities to make spatial transformation within the environment (Hegerty and Waller 2004). The ability to encode objects based on dimensional attributes and Euclidean relations is a high-level cognitive function (Mohler et al. 2013), and shifting the arrangement of objects based on hypothetical perspective changes indicates the ability to define the spatial structure of the environment based on a top-down Cartesian, or allocentric, reference frame (McNamara 2002). Fillmon (2015) describes an allocentric perspective as object-centered, stating "allocentric representations reference object locations to space external to the perceiver. For instance, positions could be represented in Cartesian or polar coordinates with the origin centered on an external reference object"(2). In the environmental perspective psychometric test, participants study a two-dimensional array of objects arranged in a circle and are asked to indicate the direction to a target object based on an imagined perspective. The data generated from the environmental perspective test serves as the independent variables to parameterize the cognitive variable *metric-location coding* in the agents. In the model, *metric-location coding* is the agent's ability to use the allocentric perspective to perform global updating of the environmental in an internal cognitive representation (Holden and Newcombe 2013) and is measured as the extent of agent global environmental knowledge during the model simulations.

The *metric-location coding* field data are generated with a perspective-changing field measure, which asks participants to indicate the direction of 12 common landmarks from two different locations in the study area (Hegerty et al. 2002). Data from the perspective-changing field test are the angular distortions between participant responses and the true direction (**Figure 8**). The data are correlated with the environmental-perspective psychometric test to evaluate the reliability of the psychometric test data to parameterize the cognitive variable *metric-location coding* in the agents. The model output of agent global knowledge is correlated with the perspective changing field data to evaluate the ecological validity of agent behaviors in the model.

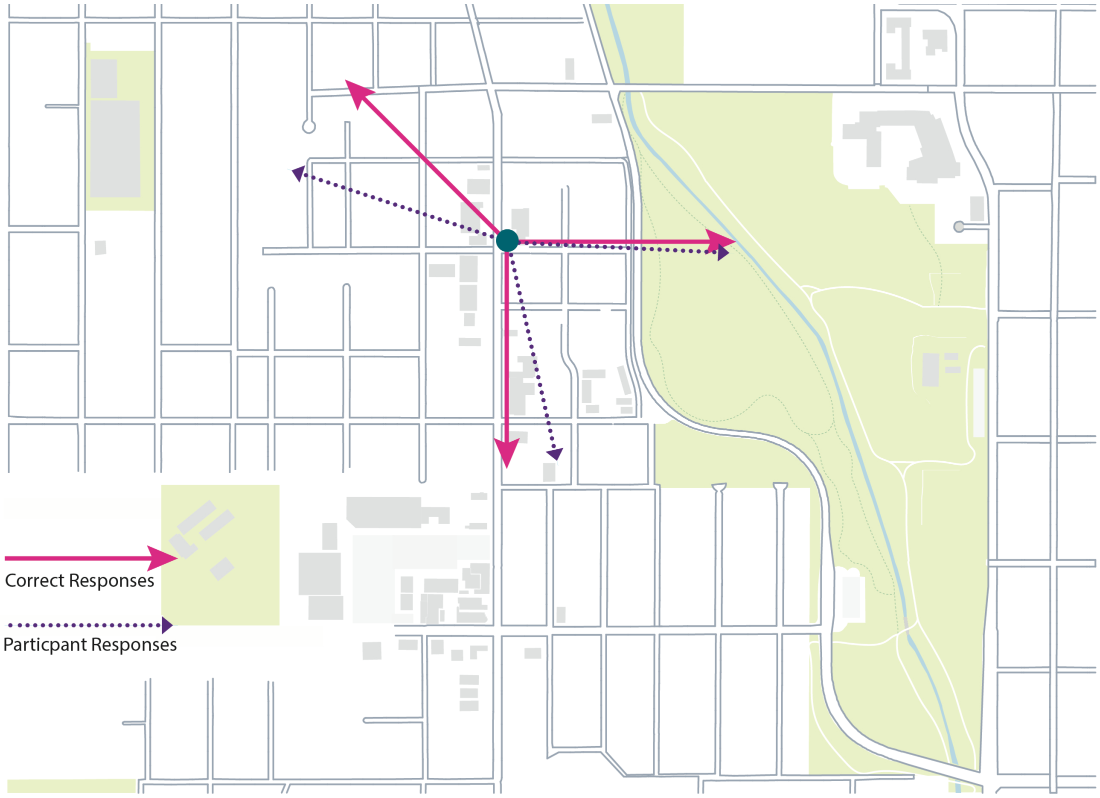


Figure 8 – Data analysis example for the perspective changing measure.

Path Integration

The fourth psychometric test used to parameterize agents is a spatial-engagement test that measures a participant's ability to construct and integrate mental representations of the environment during movement along routes, or path integration (Loomis et al. 1999): "With path integration, the traveler uses sensed self-velocity or self-acceleration to update current position and orientation in relation to some starting point" (Klaztky et al. 1998: 32). The spatial engagement test is a 65-question Likert-scale survey asking participants to rank the frequency and extent of movement in relation to material features in the built environment. Baenninger and Newcombe (1989) demonstrate the relationship between the frequency and type of spatial activity in relation to material aspects of the environment produces strong indicators of an individual's spatial abilities. Data from the survey combine perceptual and material aspects of spatial behaviors, allowing for an understanding of individual engagement, activity, and perception of salient environmental features critical for path integration. The data generated from the spatial-engagement test serve as the independent variables to parameterize the cognitive variable *path integration* in the agents. In the model, *path integration* is the agent's ability to maintain a sense of place recognition and direction of movement within an environment to create efficient routes (Loomis et al. 1999) and is measured as the amount of time the agent is navigating the environment with optimal routing behaviors.

Recording each participant's unguided navigation between an origin and destination through the study area generates the path integration field data. The route is recorded using a GPS application to create a detailed path for each participant. Direct-path movements are calculated by recording routes from each decision point (moments in the route when the participants stop for greater than 5 seconds) towards the destination and calculating the variance in the participant's route against a route optimization algorithm (**Figure 9)**. The data generated from the direct-path movement measures are correlated with the results from the spatial engagement test to evaluate the reliability of the psychometric test data to parameterize the cognitive variable *path integration* in the agents. The model output of agent optimal routing is correlated with the direct-path movement field measure to evaluate the ecological validity of agent behaviors in the model.

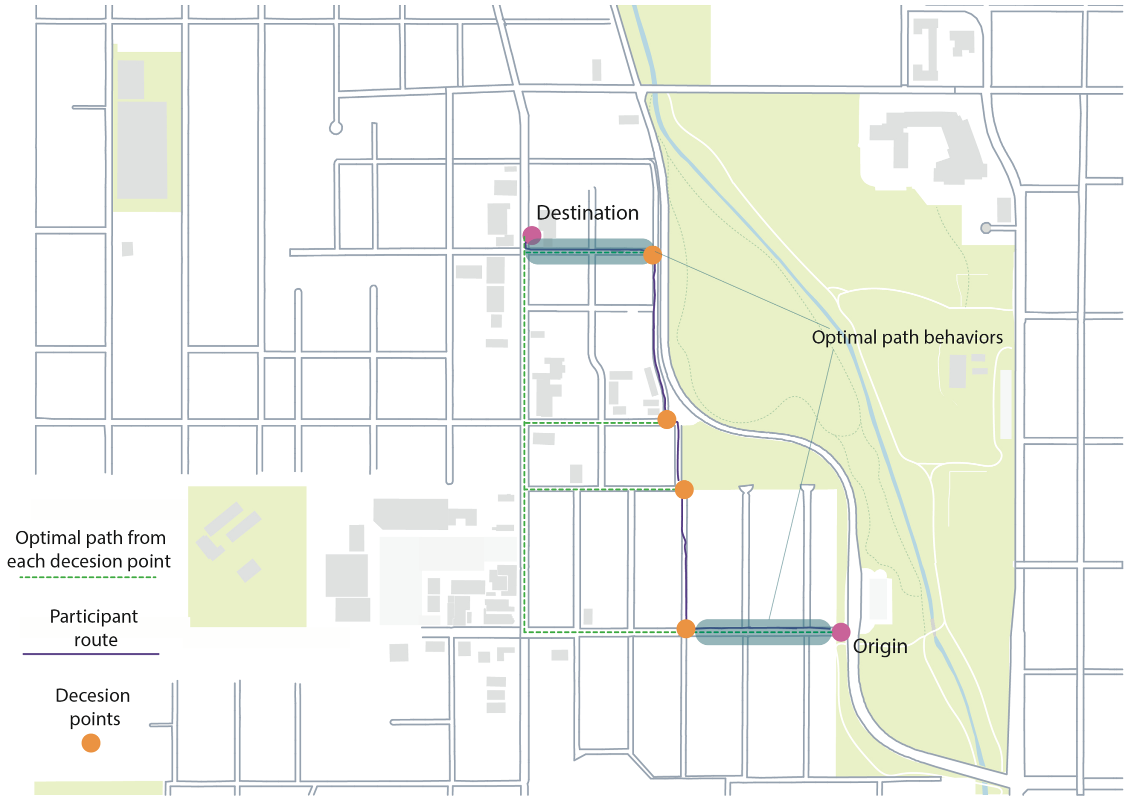


Figure 9 – Data analysis example for the direct path movement measure.

Spatial Reference Frame

The final psychometric test used to parameterize agents is the route-planning test that asks participants to describe a route between two locations based on map features, communicating the details of the route in a manner that someone without the map could use the information. Taylor and Brunyé (2013) detail how specific spatial language translates complex environments into viable mental representations. The spatial discourse of participant responses illustrates an individual's preferred representation of the environment. Data generated from the route-strategy test are recorded by asking participants to write out detailed route instructions from an origin to a destination (Denis et al. 1999). Possible routes include multiple decision points through a simple road network. Levison (1996) proposes two primary reference frames for classifying spatial language—the environment-centered allocentric perspective and the human-centered egocentric perspective. The route instructions are classified into spatial language categories of allocentric (cardinal directions, Euclidean distances) and egocentric (relative directions, topological distances). The data generated from the route-planning test serves as the independent variables to parameterize the cognitive variable *spatial reference frame* in the agents. In the model, agent-navigation strategy is measured as the as the amount of time each agent is using one of the two strategies during simulations.

The *spatial reference frame* field data is generated using the same unguided navigation data as the path integration field measure but focuses specifically on the duration and location of each stopping point. Each navigation decision point in the study area is classified according to Lynch's (1960) elements of urban space (path, edge, landmark, node, and district) to identify the most salient environmental features at each location (Millonig and Schechtner 2007). Performance at each decision point over the course of the route is classified to understand how the participant is structuring the environment (e.g. frequent short stops or infrequent longer stops). The locations and behaviors of environmental structuring allow us to build a *spatial reference frame* for each participant (e.g. 64% egocentric, 36% allocentric). The data generated from the navigation decision field measure are correlated with the route-planning test to evaluate the reliability of the psychometric test data to parameterize the cognitive variable *spatial reference frame* in the agents. The model output of agent navigation strategy is correlated with the navigation decision field measure to evaluate the ecological validity of agent behaviors in the model.

Figure 10 – Data analysis example for the navigation decision measure.

Cognitive Profiles, Model Environment, and Validation Results

There are two primary concerns in the analysis of the laboratory, field, and model-generated data. The first is to evaluate the extent to which psychometric test data of spatially explicit cognitive abilities can be used to parameterize an agent-based spatial model of everyday pedestrian behavior. Everyday pedestrian behaviors are conceptualized as moving beyond leader-follower or physics-based representations of pedestrian movement, and expending modeling representations to capture deeper cognitive and experiential aspects of walking – to transform the pedestrian from a mechanized transportation unit to a thinking, social being. The second is to triangulate the data for each cognitive variable to trace an innovative approach to ecological model validation.

Cognitive Profiles

The first step in analysis is to consolidate the repeated measures in each psychometric test to create a single value for each cognitive variable per participant, per test. First, all participant responses for each test are standardized (for example, the 12 data points for the environmental perspective test) and outliers removed. In the psychometric test, variance between subjects is often high, illustrating individual differences in cognitive processes. Within subject variance, however, is typically a more narrow range of responses within a single testing session, and outliers indicate potential measurement errors including participant distraction or the misreading of instructions, justifying the removal of outliers. Following standardization, the data from all participants are features scaled to normalize the range of independent variables to values between 0-1. The data is then used to create cognition profiles for each participant, where the results from each of the psychometric laboratory test are standardized for each of the five cognitive variables. The cognitive profiles can easily be visualized with a coxcomb plot, with the score for each test proportionally scaled outward from a central point, quickly highlighting strength and weakness within subjects and illustrating individual differences across subjects (**Figure 11**). The cognitive profile for each participant is injected into the agent-based modeling framework to parameterize agent cognition in the model design.

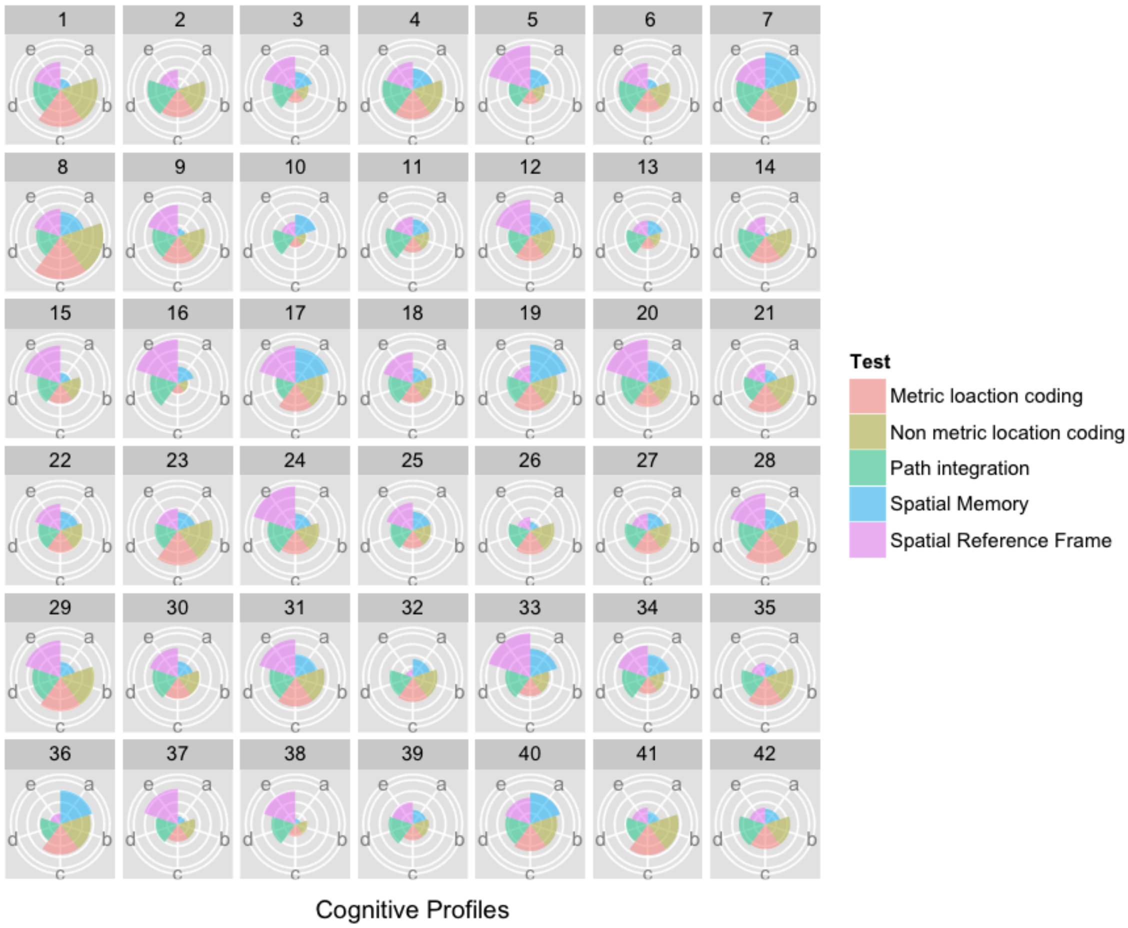


Figure 11 – Cognitive profiles with data generated from the psychometric test.

Model Environment

As the focus of representation and analysis is on deep components of agent cognition rather than a detailed analysis of structural or spatial variables, the model uses a relatively simple and straightforward abstraction of a five by six block urban street network[3]. Upon setup, 10 intersection cells and 10 random cells are given an increased perceptual salience to represent a landmarks or major intersections, which serve as reference points for agents moving through the environment (**Figure 12**).

[3] The cognitive model is loosely based on the traffic grid model (Wilensky 2003) in the Netlogo model library.

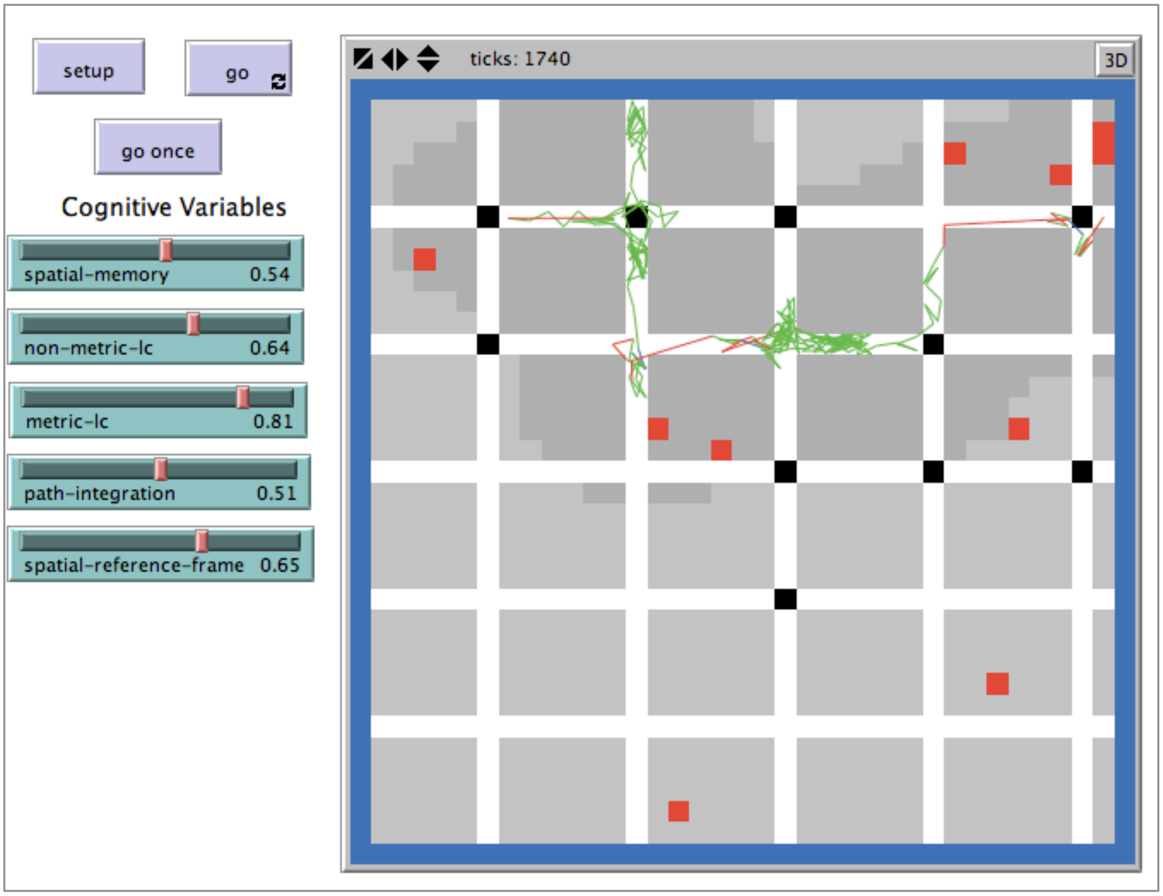


Figure 12 – Cognitive model of pedestrian agents.

The model is populated with a single agent at a time, reflecting one of the cognitive profiles established through analysis of the psychometric test. The agent moves through the model environment by navigating between locations or by engaging in social behaviors, which change randomly following a set time sequences or at the completion of intermediate goals. During navigation behaviors, agents use a wayfinding submodel to gather information from the environment to navigate from the current location to a defined location in the transportation network. Social behaviors use a localized search submodel (O'Sullivan and Unwin 2010) that allow agents to experience the urban space without goal-oriented behaviors or navigation strategies, representing experiential, social, and performative engagements with the urban space. Data is recorded for each of the previously discussed outputs reflecting cognitive task at each of the 3000 time steps and the model is simulated 1024 for each participant cognitive profile[4].

Model Validation

The model validation approach this paper takes does not attempt to confrontationally validate the final pattern of pedestrian behaviors in the model with real-world observations, but rather to ecologically validate the cognitive processes of each agent with a set of laboratory, field, and model generated data. The field data and the model outputs datasets are first both standardized to remove outliers and feature scaled to normalize the range of variables to values between 0-1, resulting in three datasets for each participant to evaluate the consistency, reliability, and validity of the model in representing cognitive variables in pedestrian agents. The psychometric data, the field data, and the model data for each of the five variables – *spatial memory, non-metric location coding, metric-location coding, path integration, and spatial reference frame* - are correlated with each other to understand the ecological consistency of the psychometric data, the reliability of model parameterization, and the ecological validity of agent behaviors in the model (**Table 4**).

Table 4 – Correlation measures between lab, field, and model variables.

Correlation Measure	**Variable 1**	**Variable 2**
Ecological consistency of psychometric data	Lab Data	Field Data
Reliability of model parameterization	Lab Data	Model Data
Ecological validity of agent behaviors	Field Data	Model Data

The scatterplot matrix of the variable spatial memory **(Figure 13)** illustrates the relationship between the three variables, indicating a strong positive correlation in the ecological consistency of the psychometric data ($r=.85$, $p<=.001$) and in the ecological

[4] The completed pedestrian cognition model – including model dimensions, documentation and metadata, and source code – can be found at OpenABM.

validity of agent behaviors (r=.81, p<=.001), as well as a moderate positive correlation (r=.67, p<=.001) for the reliability of model parameterization.

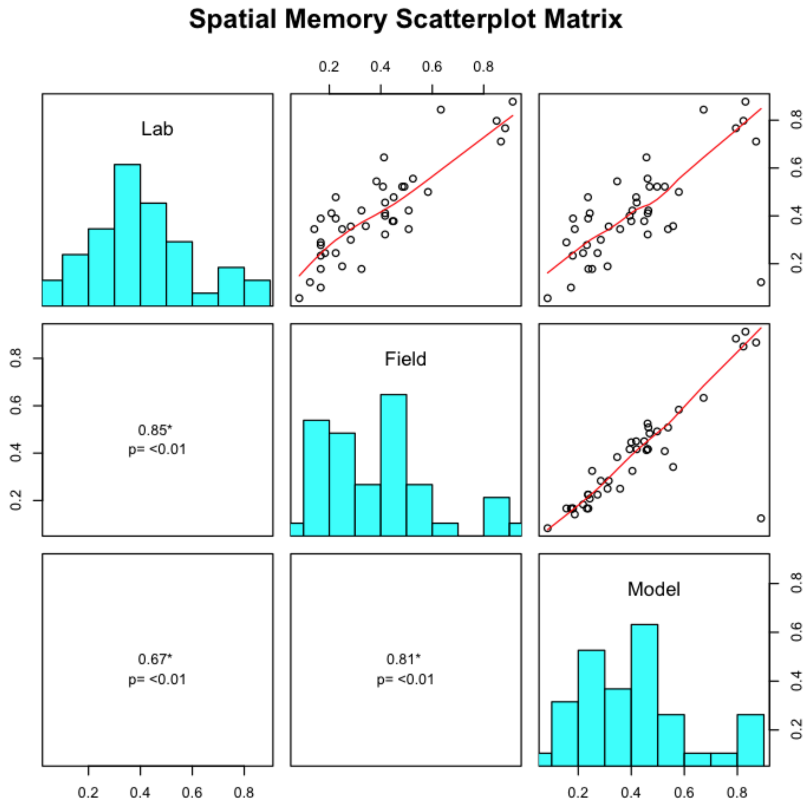


Figure 13 – Scatterplot matrix for the variable spatial memory.

The results indicate the SBSOD test is a reliable and ecologically consistent metric to obtain data for the parameterization of a spatial memory variable in the cognition of agents. Furthermore, the results indicate an agent's extent of learned local knowledge during movement is an ecologically valid representation of spatial memory in pedestrian behaviors.

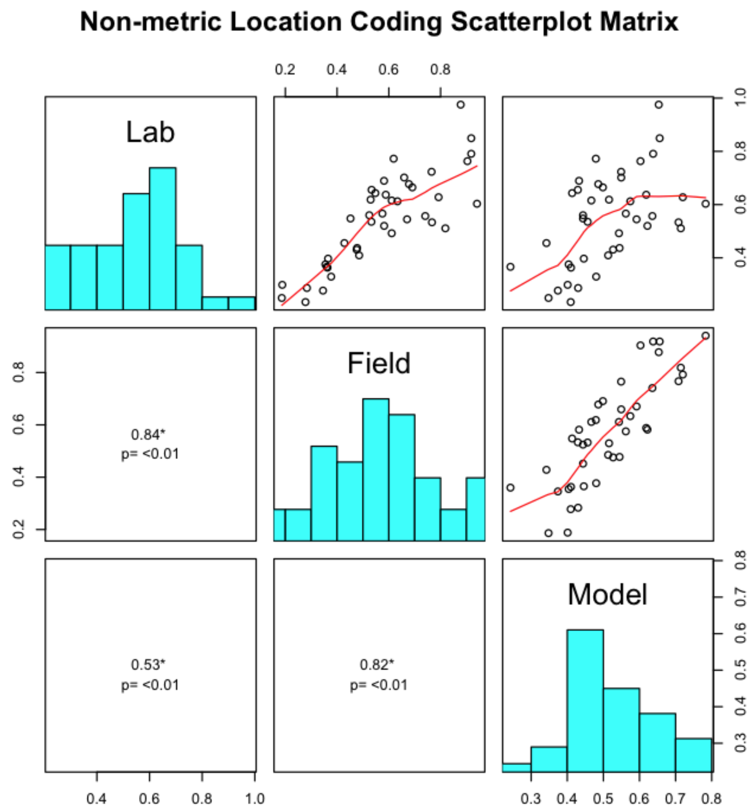


Figure 14– Scatterplot matrix for the variable non-metric location coding.

The scatterplot matrix of the variable non-metric location coding (**Figure 14**) shows a strong positive correlation in the ecological consistency of the psychometric data ($r=.84$, $p<=.001$) and in the ecological validity of agent behaviors ($r=.82$, $p<=.001$), and a moderate positive correlation ($r=.53$, $p<=.001$) for the reliability of model parameterization. The results indicate the self-location test is a moderately reliable and ecologically consistent metric to obtain data for the parameterization of non-metric location coding in the cognition of agents, though there seems to be a bifurcation of agent behaviors when the variable non-metric location coding.

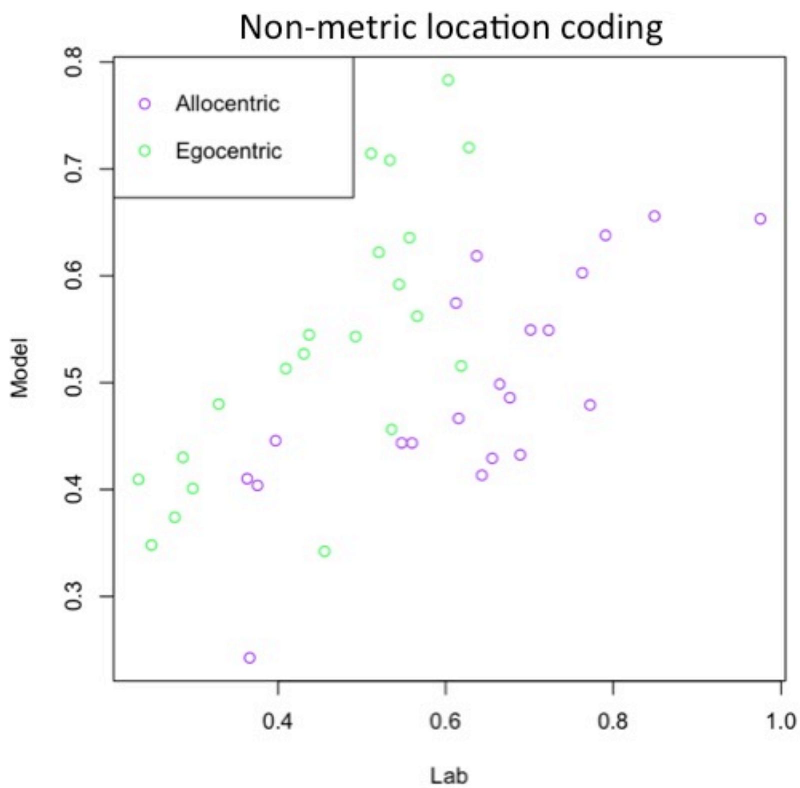


Figure 15 – Plot of model and lab results, organized by allocentric and egocentric spatial reference frames.

Non-metric location coding is measured in agent behaviors by the time the agent is searching through a first person or egocentric perspective to self-locate within the model environment. The egocentric parameter non-metric location coding largely drives this process. Another cognitive variable, spatial reference frame, parameterizes the agent to use either an egocentric or and an allocentric spatial reference frame during movement and agents with an egocentric spatial reference frame will typically outperform the parameterization of non-metric location coding whereas agents with an allocenentric spatial reference frame seem capped at a level of .65 in model performance, regardless of performance on the lab test (**Figure 15**). While this trend shows a covariance between the variables spatial reference frame and non-metric location coding, the results indicate an agent's time to self-locate in the model environment during simulations is an ecologically valid representation of non-metric location coding in pedestrian behaviors.

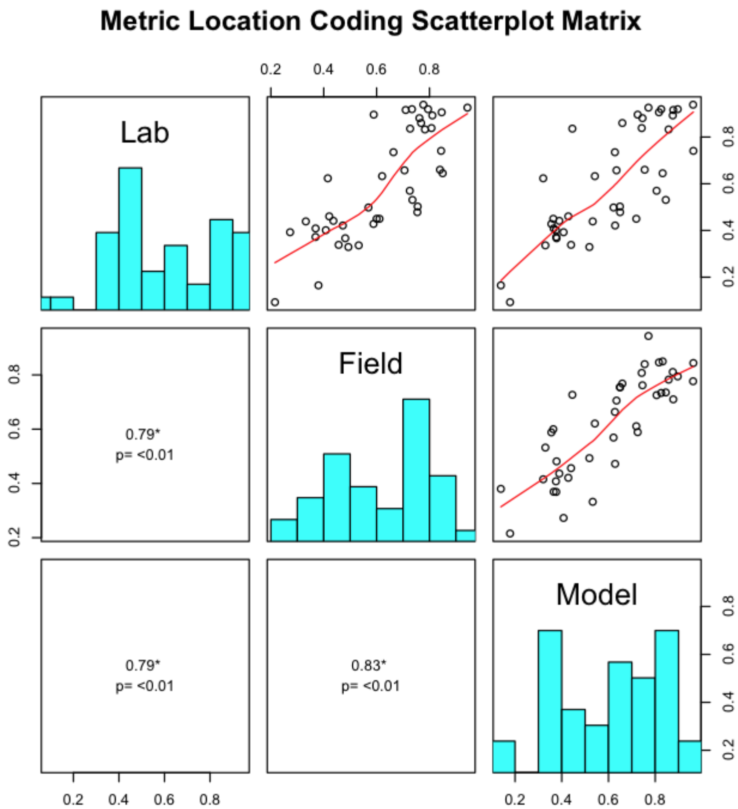


Figure 16 – Scatterplot matrix for the variable metric location coding.

The scatterplot matrix of the variable metric location coding (**Figure 16**) indicates a strong positive correlation for the ecological consistency of the psychometric data (r=.79, p<=.001), the ecological validity of agent behaviors (r=.83, p<=.001), and the reliability of model parameterization (r=.79, p<=.001). The results indicate the environmental-perspective test is a reliable and ecologically consistent metric to parameterize a metric location-coding variable in the cognition of agents. Additionally, the results indicate an agent's extent of global knowledge during movement is an ecologically valid representation of metric location coding in pedestrian behaviors.

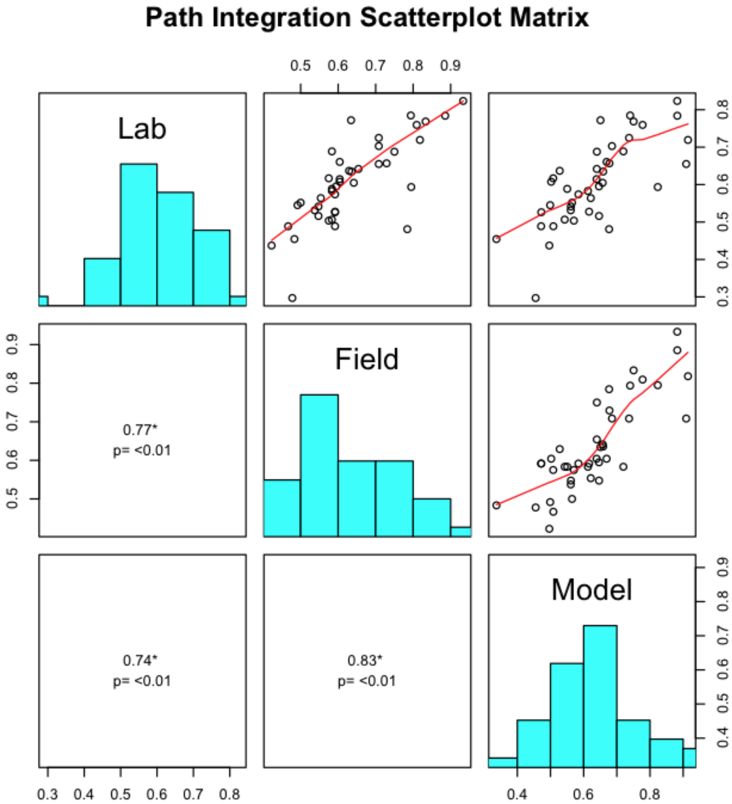


Figure 17 – Scatterplot matrix for the variable path integration.

The scatterplot matrix of the variable path integration (**Figure 17**) illustrates the relationship between the lab, field, and model outputs, indicating a strong positive correlation in the ecological consistency of the psychometric data (r=.77, p<=.001), in the ecological validity of agent behaviors (r=.83, p<=.001), and for the reliability of model parameterization (r=.74, p<=.001). The results indicate the spatial activity and perception survey is a reliable and ecologically consistent metric to parameterize a metric the path integration variable in the cognition of agents. The results also indicate an agent's instances of direct or optimal path decision-making during movement is an ecologically valid representation of path integration pedestrian behaviors.

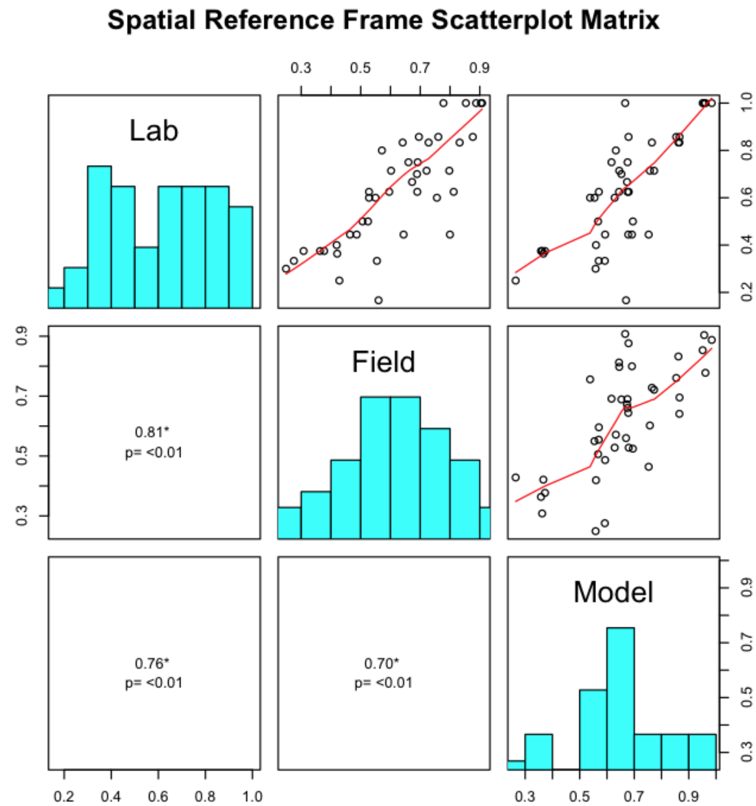


Figure 18 – Scatterplot matrix for the variable path integration.

Finally, the results of the spatial reference frame variable (**Figure 18**) illustrates the relationship between the three variables, indicating a strong positive correlation in the ecological consistency of the psychometric data (r=.81, p<=.001) and in the ecological validity of agent behaviors (r=.70, p<=.001), as well as for the reliability of model parameterization (r=.76, p<=.001). The results indicate the route-planning test is a reliable and ecologically consistent metric to parameterize the variable spatial reference frame in the cognition of agents. The results also indicate that decision point behaviors are an ecologically valid representation of pedestrian spatial reference frame. Overall, the correlation matrices illustrates the approach of using psychometric test to parameterize agent cognition, field measures to evaluate the ecological consistency of psychometric test, and model data to establish the ecological validity of agent behaviors against real-world observations is computationally robust and methodologically sound across all cognitive variables (**Table 5**).

Table 5 – Correlation scores for ecological consistency, parameter reliability, and ecological validity of the all five cognitive variables.

Cognitive Variable	Ecological consistency	Parameter Reliability	Ecological Validity
Spatial Memory	.85	.67	.81
Non-Metric Location Coding	.84	.53	.82
Metric Location Coding	.79	.79	.83
Path Integration	.77	.74	.83
Spatial Reference Frame	.81	.76	.70

While there is certainly room for expansion and refinement across all the test and variables, explicitly modeling pedestrian cognition produces both inter-subject differences and intra-subject consistency in agent representations. By explicitly modeling pedestrian cognition, this approach provides both a more realistic representation of the variability of subjects within pedestrian spaces and also a more deeper representation of individual practices, abilities, and cognitive processes that influence pedestrian behaviors. A comprehensive view across all the data illustrates the variability of responses across all participants and test, illuminating the extent of individual differences in environmental cognitive processes are and highlighting how assumptions of uniformity are not supported by data (**Figure 19**).

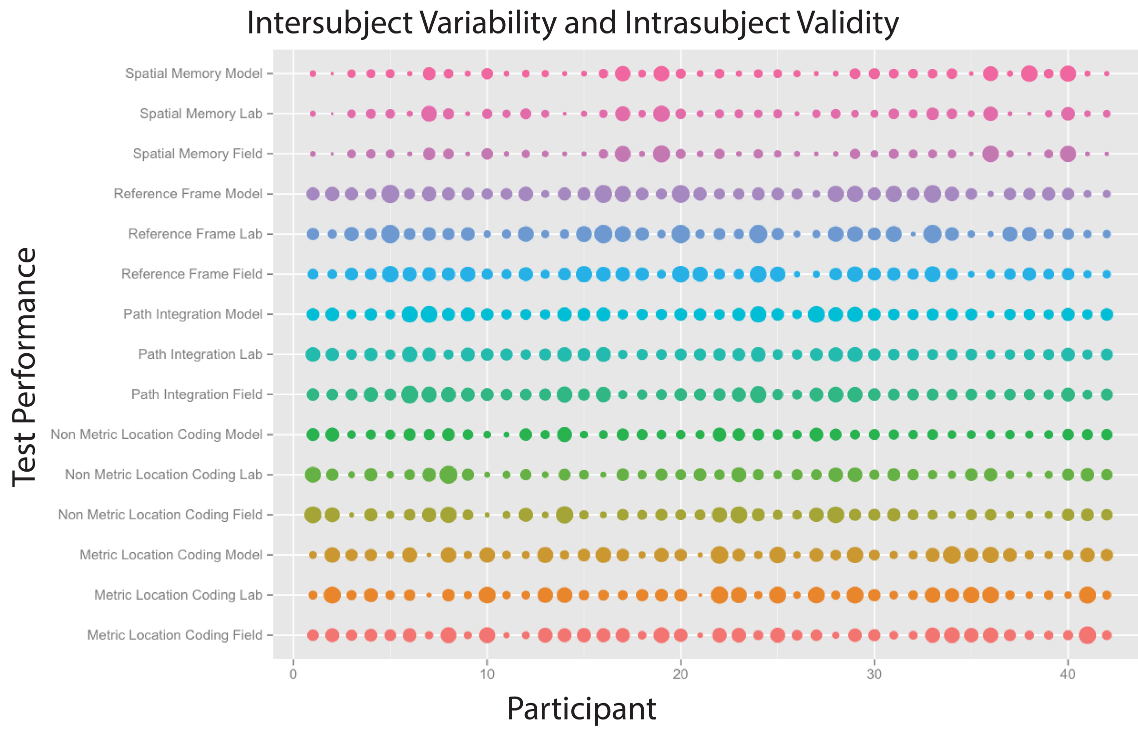


Figure 19 – Comprehensive bubble matrix of values across all participants and variables.

Conclusion

Identifying and modeling cognitive variables deepens human representations in computational agent-based pedestrian models, providing greater theoretical credibility to models depicting how pedestrians perceive, interact, and behave in urban spaces. This is especially important as practices of walking are embodied human activities, and in large part driven by cognitive, experiential, and social processes. Linking the observable patterns of human movement to internal and individual human processes is imperative, as greater understandings of human agency during pedestrian practices can have significant influences on both design practices and on analytical approaches to understand human movement. This paper illustrates that a data-driven empirical agent-based modeling approach is not at odds with a relativistic philosophy of science by creating a framework that is not reliant on generalizable observations in the parameterization of agent representations or on reductionist validation techniques to understand the model credibility in representing pedestrian activities.

The importance of developing such an approach to agent-based modeling, particularly in pedestrian and human movement models, extends beyond expanding the theoretical basis for modeling walking behaviors. First, this approach positions individual human-subject data as the basis for designing and evaluating the model, relying on small and soft datasets that specifically measure individual processes and differences. In this sense, soft datasets refer to the collection of human-centered data specifically targeting internal variables often referred to as soft within the broader scope of analytical modeling. In this sense, soft variables are not to imply data collected in a manner that is not rigorous, repeatable, accurate, or analytically precise. Rather they are variables commonly framed as hard to measure, internal, and highly flexible variables. In this sense, soft variables refer to human emotions, cognitive capabilities, and individual perceptions of the environment. Often the hard versus soft binary reflects a distinction between rigorous, repeatable quantitative data and open-ended qualitative human-centered data. The approach proposed in this dissertation rejects this binary, illustrating instead that a rigorous experimental design, consistent and reliable instruments, and careful consideration of data representations can incorporate the variables typically framed as "soft" into an analytical modeling framework. The intention of this language is to highlight agent-based modeling is not limited by data structure, and should give more consideration to the "hard to measure" variables that comprise so much of human behaviors and activities.

The approach introduced in this chapter turns attention to the individual and, rather than attempt to make generalizable claims about individuals based on aggregate population data, instead focuses on how to capture the ranges of abilities and performances across multiple ecologically consistent variables. Moving from generalizable to individual representations requires engagements with a deeper sense of cognition than is commonly employed in pedestrian models, resulting in the coding of individual entities in more meaningful way.

Finally, by understanding specifically the links between cognitive processes and pedestrian practices, this paper provides an innovative approach to understanding human processes often overlooked in conventional transportation planning and design practices. A human-centered approach to transportation design fuels the creation of spaces and systems that favor inclusion and may potentially resonate more deeply with a greater range of human experiences. The development of dynamic cognitive representations links human and artificial agents, providing a foundation to further the design individually intelligent, decision-making pedestrian agents for dynamic urban design and redevelopment simulations.

The next chapter in this dissertation takes the infusion of cognitive capabilities into agent-based models described in this chapter to look specifically at a redevelopment project in Eugene, Oregon. By having a data-driven and ecologically validated method to model individual differences in cognition into a set of pedestrian agents, the next chapter can design and implement a model to understand how potential changes to street infrastructure could impact the decision-making and spatial behaviors of real-world pedestrians. In doing so, the next chapter provides a robust analysis of both how individuals respond to changes in the built environment as well as offering a new conceptual tool to evaluate municipal redevelopment. The methods and modeling approach described in this chapter directly influence the design and level of analysis of the redevelopment case study.

CHAPTER IV
AGENT BASED MODELS IN SUPPORTING PEDESTRIAN TRANSPORTATION PLANNING AND DESIGN

Introduction

Cities across the country are struggling with how to best examine a network of street infrastructure that in many ways runs oppositional to shifting views of public health, urban transportation, and environmental sustainability. Many scholars advocate for the redesign of existing streets to a complete street design that enables safe access for all modes of transportation, maintaining that inclusive changes to street infrastructure can address the spatial mismatches in contemporary cities while increasing the public safety and walkability of neighborhoods (Ewing et al. 2006; Schlossberg 2013). Walkable neighborhoods and pedestrian-oriented design are often portrayed as simple, solution-based approaches to redevelopment that can investigate the myriad of structural and social issues in the city (Speck 2012), and scholars emphasize deeper engagements between street infrastructure and human-scale pedestrian behaviors can form a strong theoretical foundation for more sustainable urban practices (Kenworthy 2006). As the public becomes increasingly aware of walkability as a measure of urban health, scholars and practitioners are beginning to focus more attention on both the structural elements of pedestrian-oriented design as well as the human experiences in practices of walking.

Despite the increasingly acknowledged need for pedestrian-oriented redevelopment, transforming existing street infrastructure is not a straightforward process, and the human responses to such changes is complex, dynamic, and plural. Modernist approaches to planning and design have embedded a set of automobile-oriented values into our collective urban imagination, bracketing our concept of streets and rendering alternative configurations and uses difficult to imagine (Forsyth and Southworth 2008). These embedded values often lead to confusions about both individual design elements and potential system-wide impacts of proposed changes among a variety of local stakeholders. Thus, many redevelopment projects proposing to transform existing street infrastructure are met by the public with a great deal of confusion, often interrupting, delaying, or fostering resentment towards the proposed changes.

Increased financial and political pressures on local governments surrounding redevelopment, as well as the need to examine larger global issues with local initiatives, has created a need for new analytical tools to evaluate and understand how changes to the built environment might impact the everyday behaviors of citizens. In recent years, agent-based models have emerged as one possible tool to respond to the need of deeper understandings of complex human-urban interactions. An agent-based model is a computational model for simulating the behaviors and interactions of autonomous entities within a virtual environment (Grimm and Railsback 2013), serving, as Torrens (2010) explains, "as a vehicle or apparatus that allows for theory to be allied with data in some sort of analytical framework" (428). Agent-based models typically represent multiple heterogeneous agents with decision heuristics and adaptive processes, which interact with both the model environment and each other over a given spatiotemporal extent. Agent-based models are commonly used to understand how the decisions, actions, and adaptive processes of autonomous individuals impact the system's overall behavior (O'Sullivan and Perry 2013), addressing the larger need in planning for frameworks to explore ways in which small changes to the structural elements of the urban transportation system influence individual decision-making and how these individual decision-making processes scale up to impact the collective system behaviors. Within the model environment, several structural elements proposed through the planning process – including but not limited to network connectivity, land use patterns, zoning and building regulations, and environmental aesthetics – can be systematically investigated to more fully understand the impacts of proposed changes on the behaviors of heterogeneous pedestrian agents.

This paper advocates for the use of agent-based modeling to understand pedestrian behaviors and support planning decisions in response to increasingly necessary changes in the built urban environment and transportation system. Modeling pedestrian behavior is especially suited for the agent-based framework, as the practice of walking exists at different spatiotemporal scales and is not fixed to the grid in the same sense as automobile, public transit, or even bicycle transport, creating a higher frequency of individual decision-making instances during movement that is not easily reducible from observed patterns. As a result, perceptions of environmental spaces and human decision-making processes play a much larger role than in other forms of transportation.

The paper will first discuss the history and context of agent-based models in pedestrian and human movement studies, with a particular focus on how different goal-oriented modeling frameworks have been implemented in the urban context and how these illustrate different types of movement scenarios. Next, a case study of a redevelopment project in the South Willamette Street corridor of Eugene, Oregon, will be introduced, highlighting both the need for changes to street infrastructure as well as alternative concepts to meet this need. Next, an agent-based model design is described using the ODD protocol (Grimm et al. 2010) that incorporates data-driven cognitive capabilities in the design of pedestrian agents and simulated environments matching the redevelopment proposals for South Willamette Street. The results of the model simulations illustrate the need for behavioral approaches to agent design, highlighting how the concept of individual cognitive capabilities can be incorporated into computational representations of transportation systems. Additionally, the results show how official assessments of redevelopment scenarios may be seriously limited in understanding the human impacts of changes in the built environment. The paper concludes with an extended discussion about agent-based modeling frameworks for supporting transportation planning and best practices for representing the individual spatial behaviors of pedestrians.

Agent-Based Models in Pedestrian Studies

Many sustainable transportation scholars advocate for the redesigning of city streets as a primary way to examine issues on both local to global scales, proposing that pedestrian friendly changes to street infrastructure can have a positive impact on issues ranging from citizen health to climate change (Southworth 2005; Forsyth and Southworth 2008; Speck 2012). Though pedestrian movement is a complex and difficult behavior to model (Whyte 1988), understanding how people move through space has important implications in practices of architecture, urban design, emergency management, and public safety. An agent-based modeling approach to investigate pedestrian movement often provides more flexibility, usability, and behavioral realism than traditional statistical or network optimization models (Torrens 2003). One unique benefit of an agent-based modeling platforms is the ability to understand how system-wide patterns emerge from a collection of individual behaviors and interactions, often producing results and insights that would be difficult to come by from the collection of the individual parts (Manson 2001; Bennett and McGinnis 2006).

Despite the ability to represent the heterogeneous behaviors of individuals within a system, agent-based models are rarely employed in analysis and discussions about everyday individual pedestrian practice. This is due in large part not to exclusion by urban and transportation planners, but rather because the predominant way to represent pedestrian agents is rather narrow and limited. Many agent-based pedestrian models parameterize or define agent behaviors in collective rather than individualistic terms (Raubal 2001; Helbing et al. 2005; Bitgood and Dukes 2006; Torrens 2012). Ligtenberg et al. (2004) explain this design choice in the context of environmental management:

> The use of agents for the representation of organizations or interest groups rather than individual actors provides, according to us, a more realistic modeling of the process. Taking individual people as building blocks of the model does not represent the planning process and unnecessary increases the complexity of the model. Organizations and interest groups are the decision-makers at the level of multi-actor regional planning (52).

While this framing of collective versus individual representation may be true for planning issues at regional scales, aggregating individuals into singular behaviors in pedestrian modeling often fails to capture the personal and individual social motivations and cognitive processes underlying observable pedestrian behaviors. Thus, the use of generalizable agents is an appropriate representation for just two specific types of pedestrian behaviors: wayfinding models and evacuation models.

Pedestrian wayfinding models (see e.g., Raubal 2001; Turner and Penn 2002; Antonini et al. 2006) typically use a stimuli-response framework to represent pedestrian movement, creating a set of causes and effects within the environment based on agent perceptual and physiological abilities. For example, an agent within the model environment perceives an environmental feature (e.g. a landmark) and responds with a specific behavior (e.g. turn right) in order to meet a defined goal. This approach focuses on the optimization of energy and spatially dependent variables as the catalyst for agent movement across the model landscape. In other words, agent perception of the environmental affords the planning and execution of rational, goal-driven actions (Torrens 2010). Portugali (2011) argues this approach to modeling pedestrian movement, while productive in certain scenarios, embeds agents with unrealistic motivations and abilities that lead to uniform and often inflexible representations of human behavior. While models with this design have been quite effective in representing pedestrian behavior in relatively static and single-purpose spaces, such as navigation through an airport terminal (Raubal 2001) or a shopping mall (Bitgood and Dukes 2006), they are limited in capturing broader and dynamic everyday pedestrian activities by assuming all agents to be rational, goal-oriented, and equal in abilities such as locating, encoding, and using salient environmental features in decision-making.

A second common type of pedestrian modeling using group-defined behaviors is extreme event or scenario-based models, such as emergency evacuation from a building or crowd flows at a festival (see e.g., Batty et al. 1998; Helbing et al. 2001; Shao and Terzopoulos 2005). Many scenario-based models are driven by agents perceiving and mimicking the movements of other agents, resulting in a sort of flocking behavior that creates an aggregated flow of people across the built space. This type of collective movement is typically referred to as a physics design (Helbing et al. 2005) in which individuals are treated as outwardly or physically reactive to environmental stimuli. As a result, computational resources focus primarily on physiological aspects of movement, such as steering, collision avoidance, and soft-body dynamics (Torrens 2012), producing realistic-looking but not necessarily realistic-behaving gamified pedestrian agents. Typically these models represent agents homogenously in order to understand how crowds may react in certain situations or in response to different aspects of the built environment.

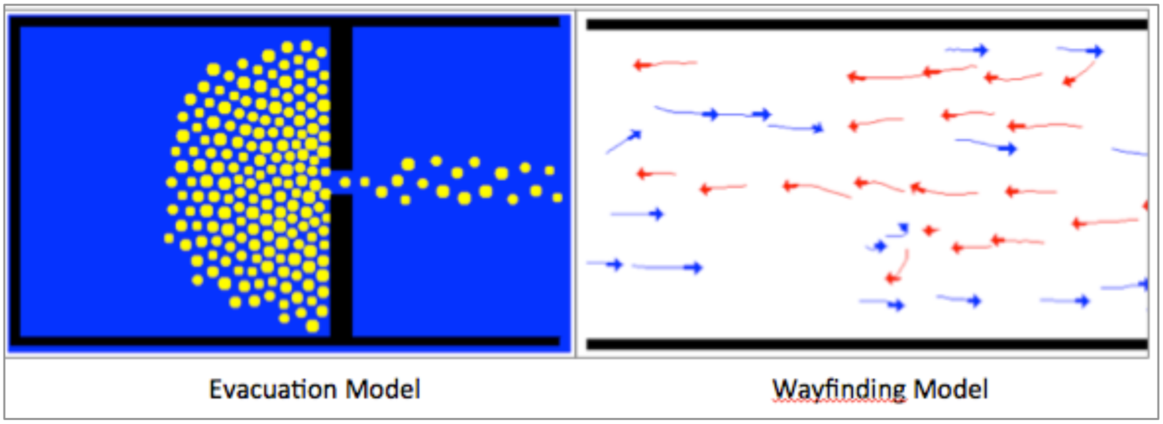


Figure 20 – Example of an evacuation pedestrian agent-based model and of a wayfinding pedestrian agent-based model. Source: OpenABM.

Both types of agent-based pedestrian models (**Figure 20**) examine different reasons and needs for human movement, illustrating the utility of aggregate approaches to explore the relationship between the environment and human behaviors. Models designed with homogenous, aggregated agent representations increases the analytical tractability of the model, providing clearer explanations of both agent behaviors as well as the system-wide outcomes (O'Sullivan and Perry 2013). For example, by having individuals flow as a group during evacuation, much can be learned about both crowd dynamics and the nature of built spaces during emergency situations.

Homogenous agent design, however, limits the range of potential behavioral outputs that may prove more insightful both in understanding individual agency as well as the complexities of the whole system (Johansson and Kretz 2012). In moving towards expanding the role of agent-based modeling in support of urban and transportation planning, this paper advocates for increased attention in representing humans as more than goal-oriented, rational, and reactive entities. To understand pedestrians beyond the limits of discrete and place-specific environments, we must work towards deeper representational frameworks that embody individual abilities and agencies rather than the collective representations common in many human-movement models. To explore this potential, I turn now to a case study of the South Willamette Street corridor in Eugene, Oregon, which is currently in the process of redevelopment with a particular focus on complete-street design to creates pedestrian friendly spaces and a walkable neighborhood.

Study Area and Research Context

South Willamette Street is typical of many streets in cities across the country—a major arterial street intersecting a medium-density neighborhood with multiple modes of transportation competing in a limited space oriented towards the automobile. The redevelopment approach of South Willamette Street – to create a complete street design inclusive of multiple uses rather than a sanctioned-off pedestrian zone typical of many pedestrian-oriented redevelopment projects – makes it critical in the study of how a diverse group of pedestrians perceive, interact, and respond to changing transportation infrastructure. In December 2013, the city of Eugene proposed the South Willamette Street Improvement Plan to improve an eight-block stretch of transportation infrastructure was in need of repair (**Figure 21**). The current configuration of a four-lane roadway with numerous driveways, obstructed and inaccessible sidewalks, and little bicycle or public transit facilities creates a relatively congested, disjointed, and, many argue, unsafe environment for pedestrian travel:

> "South Willamette Street is a multimodal corridor with a mixture of facilities to serve automobiles, bicycle, pedestrian, transit, and freight users. The challenge of providing mobility and accessibility to all users is managing various conflicts that arise, such as bikes and automobiles at driveways and turning trucks blocking travel lanes" (City of Eugene 2014).

Figure 21 – The South Willamette Street corridor, highlighting proposed changes between 24th and 32nd Ave. Pictures indicate the current state of the street infrastructure. Map: City of Eugene 2014. Photos: Julie Stringham.

In addition to addressing issues of multimodal interaction, redevelopment of the South Willamette Street must meet the often overlapping guidelines put in place by multiple agencies over the past two decades, including the Eugene Arterial and Collector Street Plan, the Eugene-Springfield Transportation Plan, and the Eugene Pedestrian and

Bicycle Master Plan, resulting in a relatively unclear long-term vision for the space. Recognizing the need for redevelopment but without a clear framework of how to design, implement, and evaluate the impacts of the proposed changes on the transportation system in this short corridor, the city enlisted a private environmental consulting firm to assess the potential impacts of street improvement under a "triple-bottom-line approach to sustainability, providing for consideration of people, the planet, and prosperity" (City of Eugene 2014: V). Subsequent analysis proved inconclusive and city officials entered public meetings with a collection of alternative concepts for South Willamette Street and little insight into how any of the proposed changes may impact, among other things, pedestrian behavior. In order to better understand how pedestrians may be impacted by structural changes in the built environment, and specifically the impacts of each of the six conceptual alternatives, this paper introduces the design and analysis of an agent-based model to evaluate the relationship between redevelopment and everyday pedestrian behaviors.

ODD Protocol of Model Design

Purpose

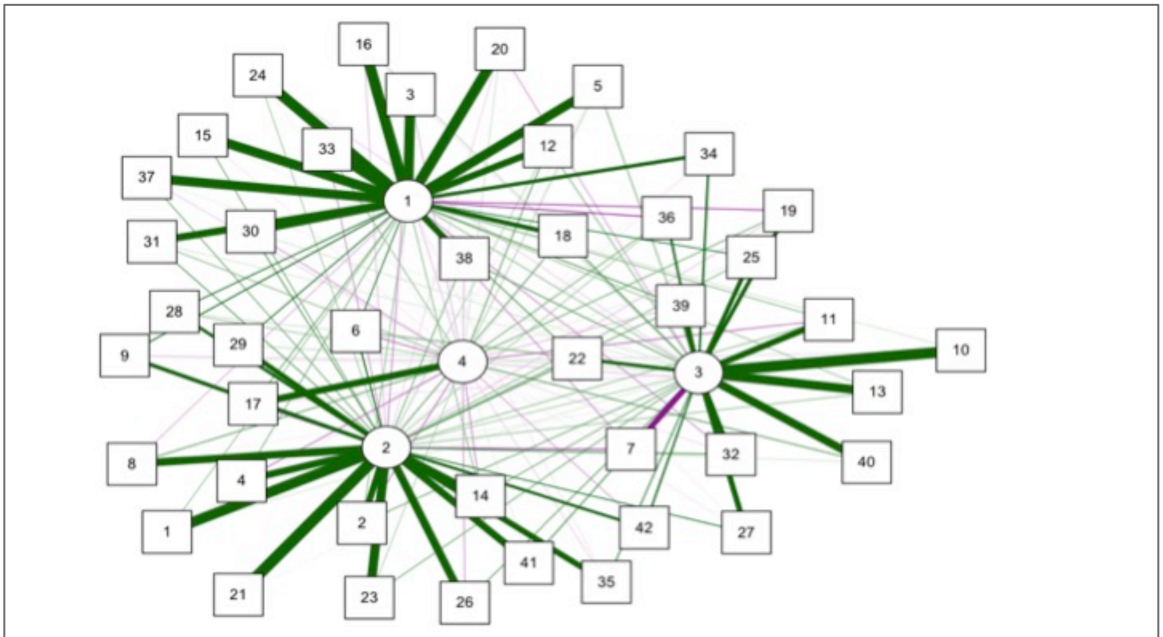
The pedestrian and redevelopment (PAR) model is a simple multi-agent pedestrian model designed to explore the effects of different municipal redevelopment plans in a simulated urban environment. Specifically, the PAR model explores the how six different conceptual alternatives of the South Willamette Street corridor will impact a population of realistic pedestrian agents.

Entities, State Variables, and Scale

The population of the PAR model is filled with agents who are parameterized with high levels of spatial and environmental cognition. Cognition is coded into agents with data generated from a set of psychometric test that specifically target the cognitive variables of spatial memory, non-metric location coding, metric location coding, path integration, and spatial reference frame. As cognitive variables are intangible constructs, they are difficult to directly measure; psychometric test are a standard approach used in the fields of environmental psychology and behavioral geography to measure an individual's cognitive capabilities and preferences, strengths and weaknesses, and overall task completion strategies (Kline 1986), and are often useful to investigate individual differences in environmental cognition and spatial decision-making processes (Allen 1999; Montello et al. 1999; Hegerty et al. 2002; Hegerty and Waller 2005).

Briefly, the cognitive variable spatial memory is an agent's ability to remember the location of objects while moving through the environment (McNamara 2002) and is measured with a 15-question sense of direction psychometric test. The cognitive variable non-metric location coding is the agent's ability to use the egocentric, first person perspective to perform a piecemeal updating of the environmental frame of reference (Wang and Brockmole 2003) and is measured with a 14-question self-location psychometric test. The cognitive variable metric location coding is the agent's ability to use the allocentric perspective to perform global updating of the environmental frame of reference (Holden and Newcombe 2013) and is measured with a 12-question environmental perspective psychometric test. The cognitive variable path integration is the agent's ability to maintain a sense of place recognition and direction of movement within an environment to create efficient routes (Loomis et al. 1999) and is measured with a 65-question spatial engagement survey. The cognitive variable spatial reference frame is an agent's ability to use move between an egocentric and an allocentric perspective when conceptualizing the environment (Taylor and Brunyé 2013) and is measured with a route-planning test. The suite of cognitive test was administered to 42 participants in July 2015.

Building an agent-based model with 42 different pedestrian types, however, is likely to produce conflated and intractable results, adding unnecessary complications to an already complex set of human-urban interactions. Rather than using the direct scores from the five different psychometric tests to directly parameterize the agents in the model environment, the participant test data is reduced with a principal component analysis to find a new set of desirable variables that efficiently represent the information in the original participant dataset. A principal component analysis highlights the underlying structure of the data, reducing the dimensions of a dataset (Abdi and Williams 2010). Principal component analysis reduces the overlapping observations in a dataset, creating a new set of variables that explains the variance and natural groupings of the dataset. This method is particularly useful for coding computation representations of human behavior from individual data sets. Human subject data varies over a number of factors, including spatial and temporal conditions, often creating datasets not easily transferred to model frameworks (Freeman 1992). Reducing the 42 participants to four pedestrian types based on the grouping of the data allows for the agent-based model to be both more analytically tractable across different spatial locations, but also to be scaled to different geographic extents (**Figure 22**).



	Comp.1	Comp.2	Comp.3	Comp.4	Comp.5
Standard deviation	4.7984217	3.2925254	2.3601648	1.60126444	3.506220e-08
Proportion of Variance	0.5482107	0.2581125	0.1326280	0.06104876	2.927043e-17
Cumulative Proportion	0.5482107	0.8063232	0.9389512	1.00000000	1.000000e+00

	Comp.6	Comp.7	Comp.8	Comp.9
Standard deviation	3.136586e-08	3.135398e-08	3.063783e-08	2.950215e-08
Proportion of Variance	2.342422e-17	2.340647e-17	2.234945e-17	2.072326e-17
Cumulative Proportion	1.000000e+00	1.000000e+00	1.000000e+00	1.000000e+00

Figure 22 – Principal component analysis of scores across all test for the 42 participants, reduced to four primary groups based on performance across scores the five psychometric tests.

A simple plot of the mean performance for each psychometric test across the four groups (**Figure 23**) clearly indicates different cognitive strategies and abilities across all the participants, allowing for a meaningful and data-driven classification of individual participants into pedestrian types. Group 1 exhibits high scores in the spatial memory and metric location coding tests, indicating a strong ability to remember the location of objects in the environment and use an allocentric or top-down perspective. Group 1 is classified as *purposeful walkers* to represent objective-driven pedestrians in the model environment. Group 2 exhibits high scores in non-metric location coding and spatial reference frame, indicating a strong ability to use an egocentric or first person perspective. Group 2 is classified as *social walkers* to represent more-than objective-driven pedestrians. Group 3 exhibits strong performance in across all tests and is classified as *experiential walkers* to represent individuals who shift between objective-driven and more-than objective driven practices. Group 4 exhibits low scores across all tests as is classified as *wanderer walkers* to represent random pedestrian behaviors. Each pedestrian type uses a different submodel to direct individual movement in the model environment.

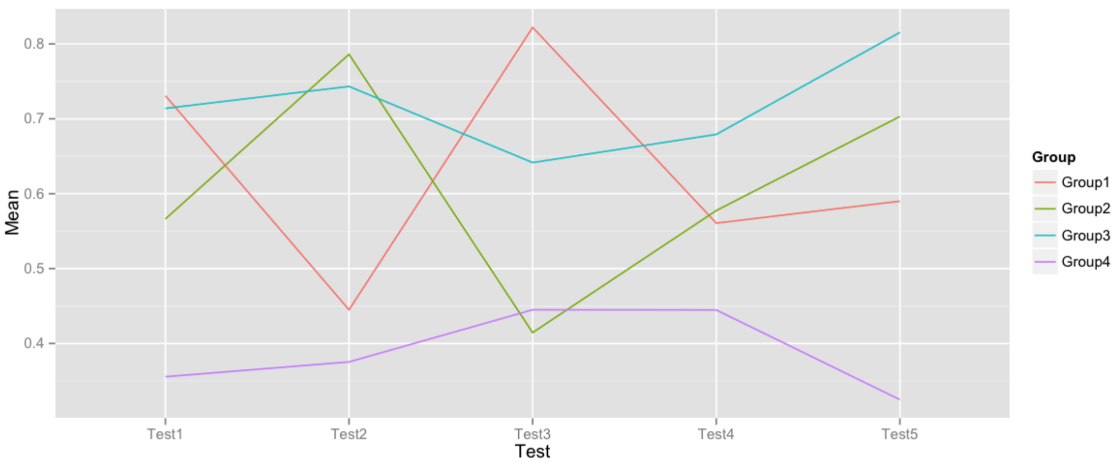


Figure 23 – Mean performance for each psychometric test across the four groups.

It should be noted the classification of agent types from cognitive data is not to say participants classified a certain way will exhibit the associated capabilities, strategies, and behaviors during all pedestrian activities. Cognitive performance at any given time relies on a multitude of factors, many of which are immeasurable with psychometric test. Rather the data indicates that during this discrete set of test, participants exhibited a set of cognitive capabilities across multiple measures, which can be classified into pedestrian types for the purpose of coding the model and making a more meaningful representation of a heterogeneous population within the model environment. During model setup, agents are assigned one of the four pedestrian types based on the proportion of variance for each principal component. The cognitive capabilities of the agents for each of the five cognitive variables are assigned using a random value within one standard deviation of the mean for each pedestrian type, allowing the population of the model environment to scale up from the number of participants while maintaining realistic human cognitive capabilities in the agents.

The PAR model environment is a horizontally oriented five-block by three-block urban streetscape populated with cognitive pedestrian agents, private automobiles, and bicycles[5]. Automobiles and bicycles travel along the gridded road network at various rates of speed, stopping at traffic signals and operating unaware of the pedestrian agents. The spatial resolution of the PAR model is 1 pixel = 20 feet and the temporal resolution is 1 time step = 2 seconds. Each simulation runs for a total of 2500 steps. Grid cells are classified as street, sidewalk, crosswalk, or development, based on the spatial configurations of the various conceptual alternatives for redevelopment, and remain constant over the course of each simulation.

Process Overview and Scheduling

The PAR model measures how each agent moves through the environment and interacts with the different features of proposed redevelopment. Different rule-based spatial movement submodels for each pedestrian type drive this human-urban interaction and the model directly measures how the agents respond to structural change in the built environment. The model environment can be altered with four parameters highlighted by qualitatively coding the six conceptual alternatives for street redevelopment outlined in the proposed South Willamette Street Improvement Plan.

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5 The model described in this paper is loosely based on the traffic and crowd town simulation model (Lukas 2014) and the traffic grid model (Wilensky 2003). The PAR model – including model dimensions, documentation and metadata, and source code – can be found at OpenABM.

Design Concepts

Basic Principles

The PAR model measures the interactions between pedestrians and the material environment. A different submodel drives the movement of each pedestrian type, and thus individual behaviors are impacted from encounters with the different structural elements of redevelopment. For example, *purposeful walkers* are more highly impacted by dimensional and metric elements of the environment whereas *social walkers* are more highly impacted by non-metric and community-based changes.

Emergence

The PAR is designed to explore how different individual pedestrian practices respond to different types of street redevelopment. The emergent outcomes from the model are the positive and negative encounters with redeveloped spaces on each of the pedestrian types. Positive encounters include interactions in which the environment affords the meeting of specific goals or the environment is perceived by agents as safe, aesthetically pleasing, and inclusive. Negative encounters include those in which the environment does not afford meeting specific goals, close interactions with other modes of transportation, and when agents view specific places in the environment as uninviting or exclusive.

Adaptation

As each model simulation represents a single trip, agents in the PAR model have relatively simple adaptive traits. *Social walkers* adapt to the spatial distribution of other agents and tend try to stay within groups of a certain size. *Experiential agents* adapt to the environment and revisit places where external reward or pleasurable experiences are found.

Objectives

Three of the four pedestrian types have movement objectives, while *wanderer* agents do not. *Purposeful walkers* are goal-driven agents and navigate from point to point in a relatively linear and straightforward manner based on environmental information. *Social walkers* have the objective to be within certain size groups of people and will tend to stay close to others once meeting in the environment. *Experiential agents* tend to search for desirable or pleasurable places in the environment, though the location or route to get to a particular location is not necessarily linear or predictable.

Learning

Purposeful and *experiential walkers* both make relatively simple mental maps of the environment, learning either efficient routes between places or desirable places in the environment through personal interaction. The information learned in a single model run is not carried over to subsequent runs, however, and all agents at the beginning of each run have no knowledge of the environment. Global knowledge can be partially or fully learned throughout the coarse of the simulation based on the cognitive capabilities of each agent.

Sensing

All agents sense the local environment visually through the course of the simulation. All agents have vision that extends up to five pixels, or 100 feet within a vision radius of 90 degrees.

Interaction

Agents interact with each other and with the environment throughout the course of the simulations. Agents interact with other modes of transportation by stopping at crosswalks and waiting for the light to turn and traffic to stop before crossing the street. Agents interact with the environment by either having positive or negative reactions to different types of redevelopment, frequenting places of positive interactions and avoiding places of negative interactions. Positive and negative interactions are defined for each agent types and are driven by the configuration of the environment, the proximity of pedestrians to other forms of transportation traveling at high rates of speeds, and to whether or not individual goals are met. *Purposeful walkers* interact with the environment by using different environmental features as clues to locate efficient routes in wayfinding behaviors. *Experiential walkers* interact with the environment by discovering and revisiting desirable places. *Social walkers* interact with each other by frequenting places with larger concentrations of other *social walkers.*

Stochasticity

The initial location of each agent in the PAR model is random as is the initial direction of movement. Once each agent has begun gathering information from the environment, movement no longer is random with the exception of *wanderer walkers*, who always have random movements.

Observations

The data collected from the PAR model illustrate the positive and negative impacts of the different redevelopment scenarios on each of the pedestrian types. Data are collected at each time step of each simulation, and all data recorded is used in analysis.

All data outputs for the impact of the different redevelopment scenarios are feature scaled to range from 0 to 1 for each agent type (**Figure 24**).

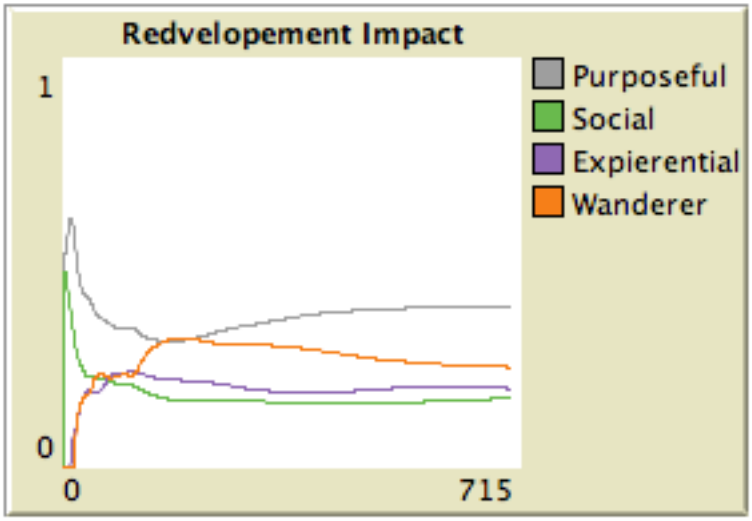
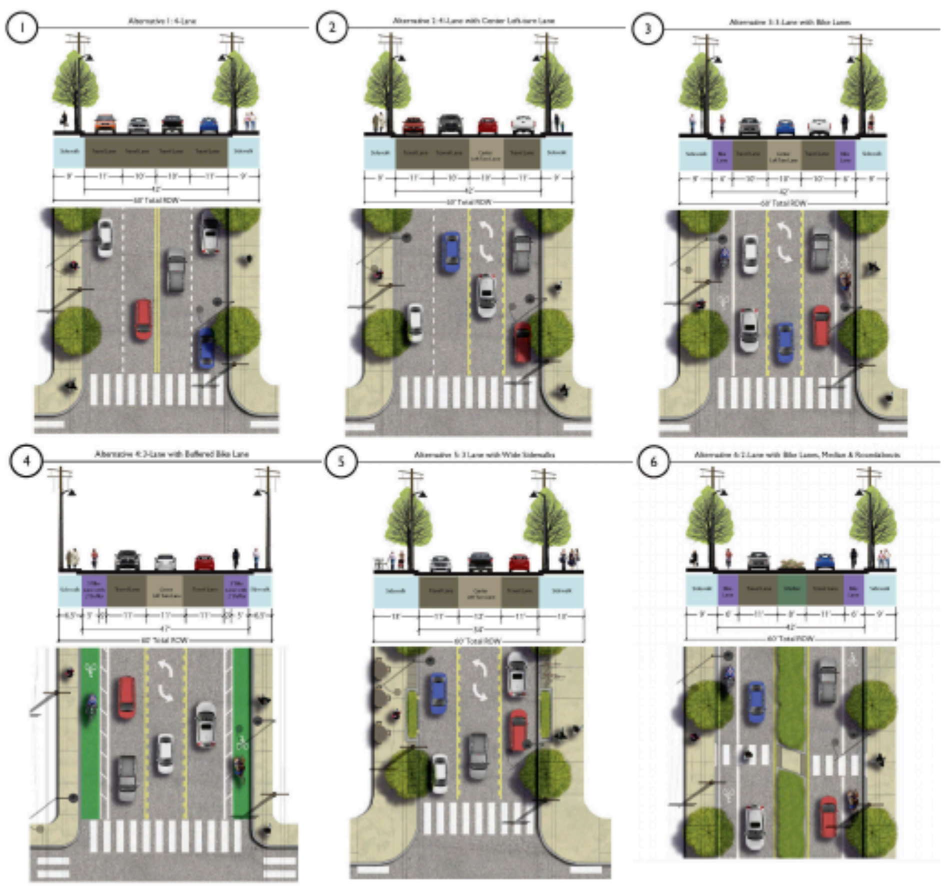


Figure 24 – Sample observations of emergent outputs in model environment.

Initialization

At time step = 0 the agents are randomly placed on the sidewalk cells in the model environment. The model environment is set up according to the four environmental parameters – dimensional, shared space, economic, and community. The parameters range from 0-1, representing a percentage of redevelopment in each category. The default position for each parameter is .5, representing current material conditions.

Input Data



Conceptual Alternatives (Tier 1)

Figure 25 – The six alternative concepts proposed by the city of Eugene to redevelopment South Willamette Street between the 24th and 32nd Streets. Source: City of Eugene 2014.

The South Willamette Street Improvement Plan is a redevelopment strategy to improve the eight-block stretch of transportation infrastructure in Eugene, Oregon. In November 2012, six conceptual alternative configurations (**Figure 25**) of South Willamette Street, following an unsuccessful private evaluations, was introduced to the public to create a strategy by the second meeting to evaluate each of the alternative designs. During the second meeting, both the Eugene City Manager and the Transportation Community Resource Group endorsed a formal screening criterion to quantitatively evaluate the alternative concepts, focusing on social, environmental, and economic impacts of redevelopment.

The formal screening criteria calculated scores from the six conceptual alternatives on 23 different measures across eight categories – *Access and Mobility, Safety and Health, Social Equity, Economic Benefit, Cost Effectiveness, Climate and Energy, Ecological Function,* and *Community Context*; 18 of the identified measures received a score as part of the formal assessment (**Table 6**). The formal assessment used a quantitative assessment, coding values of -1 to indicate negative changes, 0 to indicate no change, and +1 to indicate positive change. The sums of scores across all 18 measures create an index to evaluate the impact of each alternative concept.

Table 6 – Qualitative coding of the 18 measure assessment performed by the City of Eugene. Green indicates dimensional variables, yellow public improvement safety variables, blue economic benefit variables, and pink community support variables.

Alternative		1	2	3	4	5	6
Access and Mobility	Neighborhood connectivity			1	1		1
	Motor vehicle travel time			-1	-1	-1	-1
	Active mode travel time			1	1		1
Safety and Health	Safety			1	1	1	1
	Security			1	1	1	1
	Emergency response			-1	-1	-1	-1
Social Equity	Equity			1	1	1	1
	Economic access			1	1	1	1
Economic Benefit	Freight mobility			-1	-1	-1	-1
	Walkable/bikeable			1	1	1	1
	Business vitality		1				-1
Cost Effectiveness	Fundability	1			-1	-1	-1
	Asset management	1	1	1	1	1	1
	Project benefits	1	1	1	1	1	1
Climate and Energy	Pedestrian facilities				-1	1	
	Bicycle facilities			1	1		1
	Transit facilities					1	
Community Context	Community vision				-1	1	
Total		**3**	**3**	**7**	**4**	**6**	**5**

The primary concern with this assessment is the assumption all variables have equal impact on the system as a whole. Rather than follow assumptions of linearity and accept that all inputs have equal weight on the final output, the PAR model allows for a more in-depth and nuanced exploration into the various combinations as well as the nonlinear processes that may indicate the relative strength of different variables and how unique combinations or arrangements of redevelopment practices could produce unexpected outcomes to the pedestrian agents in the model. The model environment is parameterized by qualitatively coding the 18 established measures into four categories that reflect the type of structural change – dimensional changes, public safety improvement, economic benefit, and community support. Classification of each of the six alternative concepts creates a set of environmental values that are coded directly into the PAR model environment based on the scores from the official assessment across the four coded categories, creating six model environments based on municipal plans. In additional to the six alternative concepts, a parameter sweep is run by iteratively changing each variable by .1 while keeping all other variables constant in order to understand how the pedestrian agents respond to each environmental parameter

Submodels

A different movement submodel drives the behaviors for each agent type in the PAR model. *Purposeful walkers* use a wayfinding submodel in which each agent perceives discrete environmental features, such as a landmark or a specified intersection, and responds with a behavior to meet a goal (see e.g., Raubal 2001; Turner and Penn 2002; Antonini et al. 2006). The wayfinding submodel represents individuals engaging in directed, purposeful walks between two points in the environment. *Social walkers* use an entity-interaction submodel in which local interactions with other *social walkers* is reinforced, causing small groupings of agents over time (Vicsek et al. 2008). The entity-interaction submodel represents individuals moving through the environment with intentions of being social with other individuals, rather than navigating to a specific location. *Experiential walkers* uses a localized search submodel (O'Sullivan and Unwin 2010) in which interactions with particular environmental features creates a positive feedback for the agents, motivating them to visit the location again during the model run. The localized search model represents individuals moving through and learning about desirable places in the environment to revisit for non goal-driven reasons, but rather because they are enjoyable or beneficial for whatever reason. *Wanderer walkers* use a random walk in which movement is not guided by anything but random decision-making, representing individuals who simply walk through the environment.

Results and Discussion

Part 1: Representing Human Pedestrians

Due to the complexity and difficulty of modeling human movement, many computational pedestrian models strip away elements of individual agency, favoring the representation of human agents as responsive or reactive to external environmental variables. The PAR model uses a data-driven approach to code cognitive variables as means to represent individual agency in the model, aiming to achieve a deeper and more complete representation of human capabilities (O'Sullivan 2008). Parker et al. (2003) state, "the term cognition ranges in applicability to situations ranging from relatively simple stimulus-responses decision making to the point where actors are proactive, take initiative, and have larger intentions" (317). In the PAR model, cognition is conceived of as a high-level function, which guides the classification of the pedestrian type submodels and the individual level interactions between environmental features and agents. Model simulations under baseline conditions revel how the different data-driven pedestrian types respond and interact with different environmental variables through the course of pedestrian movement (**Figure 26**).

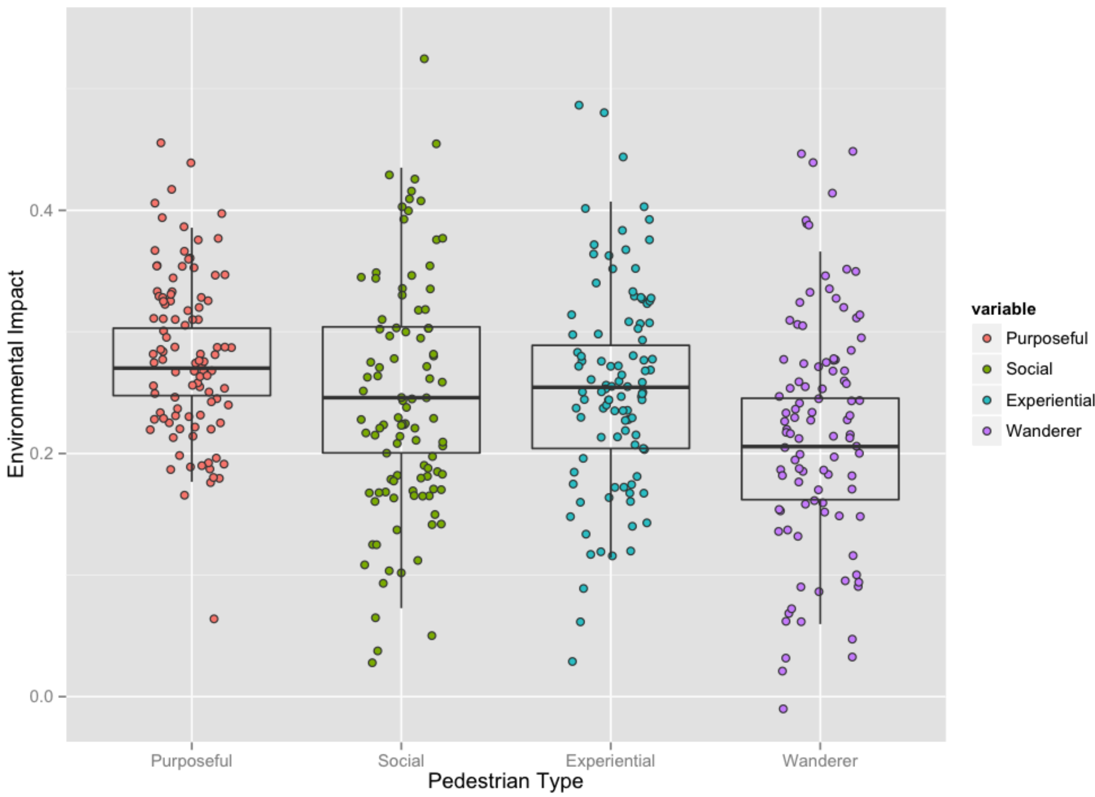


Figure 26 – Impact of baseline environmental conditions across four walker types.

Incorporating a range of pedestrian cognitive capabilities into an agent-based modeling frameworks echoes the theoretical approaches of behavioral geographers, who argue that understanding different types of human decision-making processes and observable spatial movements in the environment is best known from the study of individual differences in the internal or cognitive processes (Golledge and Stimson 1997). Mark et al. (1999) provides a framework to understand how individuals perceive, cognitively transform, encode, and articulate the perceived external world (**Figure 27**).

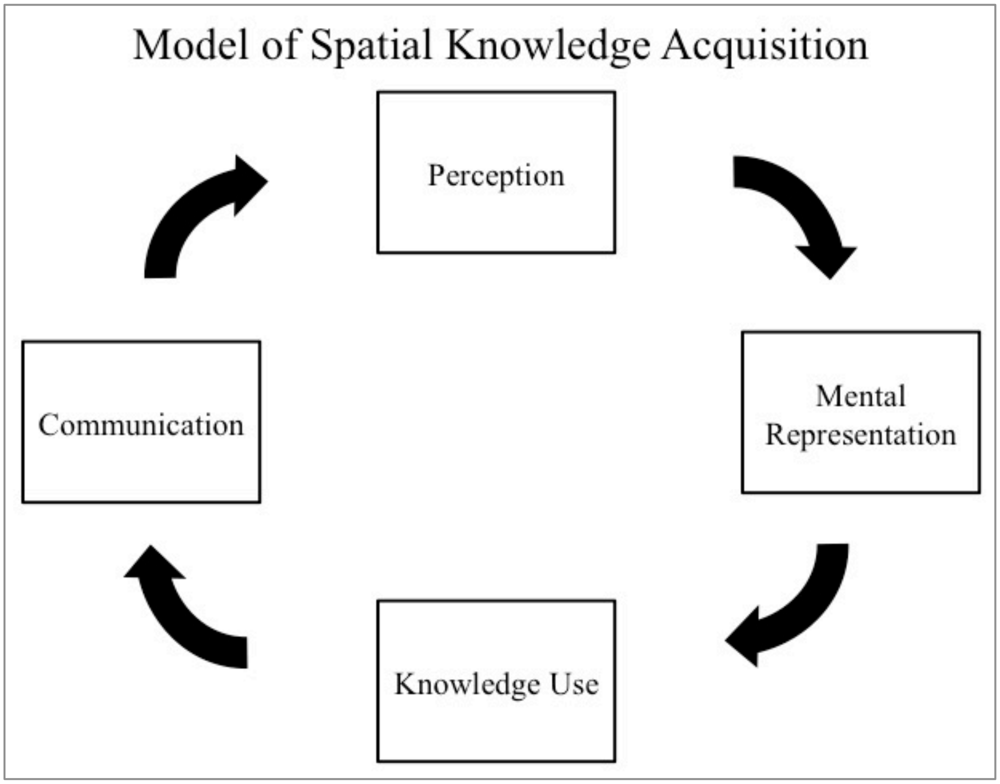


Figure 27 – Model of spatial knowledge acquisition illustrating the relationship between the perception, transformation, decision-making, and spatial behavior.

The first step in this theory of spatial knowledge acquisition is the sensory perception (sight, sound, touch, etc.) of the external environmental by an individual (this is the stage in which the majority of pedestrian models stop). The external perception of the world is then internally transformed into a mental representation of the environment. The quality, extent, and completeness of the transformation from external to internal varies from person to person based on a multitude of cognitive, sociocultural, biophysical, and spatiotemporal factors. The mental representation, or individually constructed knowledge of the environment, is then used in a decision-making process. Knowledge use again varies dramatically from person to person, ranging from subversive to goal-oriented motivations. Finally, spatial knowledge is articulated and communicated either through language, movement, or another type of spatial behavior. This framework provides a clear way to define the cognitive capabilities of each agent type in the model environment **(Table 7)**.

Table 7 – Pedestrian types classified in a spatial knowledge acquisition framework.

Agent	Perception	Mental Representation	Knowledge Use	Communication
Purposeful	Vision	Rational	Optimization	Wayfinding Walk
Social	Vision	More-than-rational	Attraction and repulsion	Entity-interaction
Experiential	Vision	Cognitive map	Self constructed	Localized Search
Wanderer	Vision	Ephemeral	Impetuous	Random Walk

An agent-based modeling platform provides the opportunity to explicitly model cognitive processes and to orient pedestrian representations towards more theoretically realistic human-centered approaches. As opposed to more generalizable representations of pedestrians, agent-based models allow for the investigation of pedestrian practices based on a multitude of motivations, capabilities, emotional states, and past experiences. In this sense, agent-based modeling can help address the 'wicked' problem of transportation planning and, more specific to pedestrianism, how to balance the technical and human components of a system. Turning attention to the human component, the model illustrates how different cognitive capabilities produce a range of interactions with the environment (**Figure 28).** The results show these interactions sometimes overlap and sometimes are unique to the individual, illustrating that homogenous or singular representations of individuals in a transportation system makes a great deal of assumptions about the practices and behaviors of the individuals. In other words, the emphasis on the technical components inherent in modernist transportation planning overlooks many important individual and human factors.

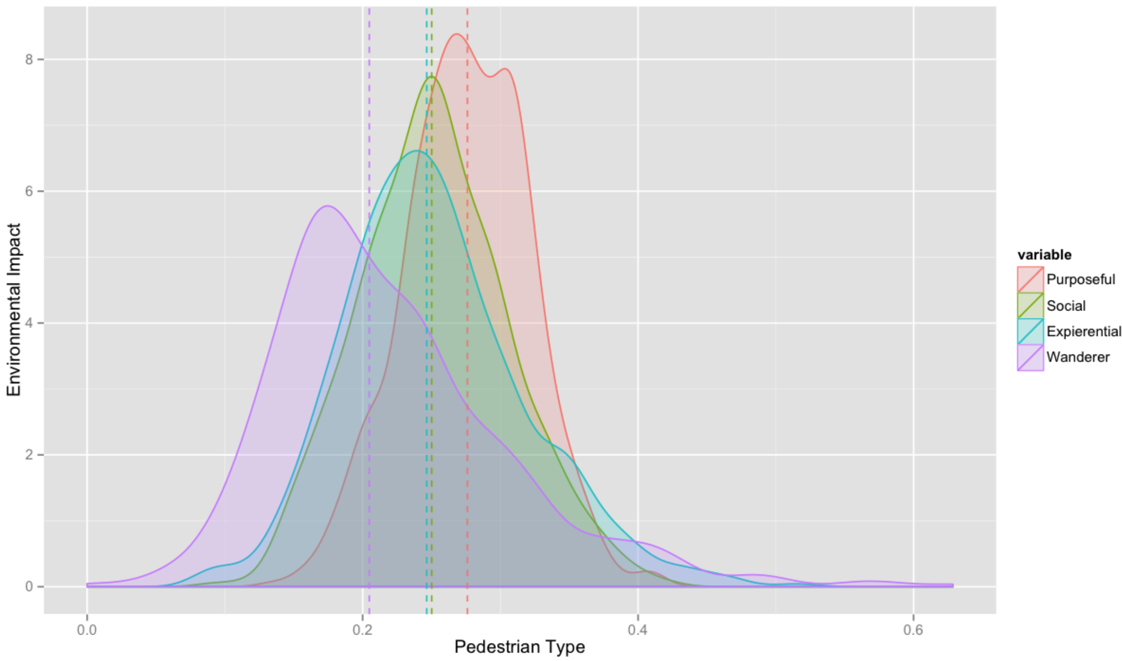


Figure 28 – Range of pedestrian interactions with the built environment across all simulations illustrates both the individual and overlapping in interactions with the built environment in pedestrian movement.

Modeling pedestrian behavior from a human-centered perspective provides an entry point to understand and analyze the relationship between the conceptualized spaces of scientist, planners, and architects and the lived spaces or users and inhabitants (Lefebvre 1991). A human-centered approach is to embrace the individuality of the human subject, endowing the individual with agency as a way to link human and artificial representations in an analytical framework. Heterogeneous agent representations embrace the concepts of individual differences in cognitive capabilities and the myriad of social motivations inherent to human-centered planning practices. Alternatively, reducing human agency to the most technical and generalizable of terms, as is the case with the majority of pedestrian agent-based models, embraces a configurational planning approach (Sepe 2010) that focuses on the structural aspects of the environment, which, in most cases, is likely better represented by the more traditional statistical, site-suitability, or linear models. With elements such as memory, cognition, adaptation, mental maps, and changing motivations, human elements of everyday pedestrianism can easily be incorporated into an agent-based modeling framework.

Part 2: Impacts of Redevelopment on Pedestrians

In addition to illustrating differences in agent behavior, the PAR model is also able to explore the human impacts of different structural elements. The formal criteria screening of redevelopment variables identifies 18 separate measures, which have been classified into four categories that reflect the type of structural change: dimensional changes, public safety improvement, economic benefit, and community support. Dimensional changes include the variables of neighborhood connectivity, motor vehicle travel time, active mode travel time, and walkable/ bikeable business district. The defining feature of this classification is the effect of the change in configuration or dimensions of the material environment on different modes of movement. The results from the model indicate that iterative changes to the dimensions or configurations to the material environment has a positive impact on *purposeful walkers*, but has little to no effect on other types of pedestrian practices **(Figure 29)**.

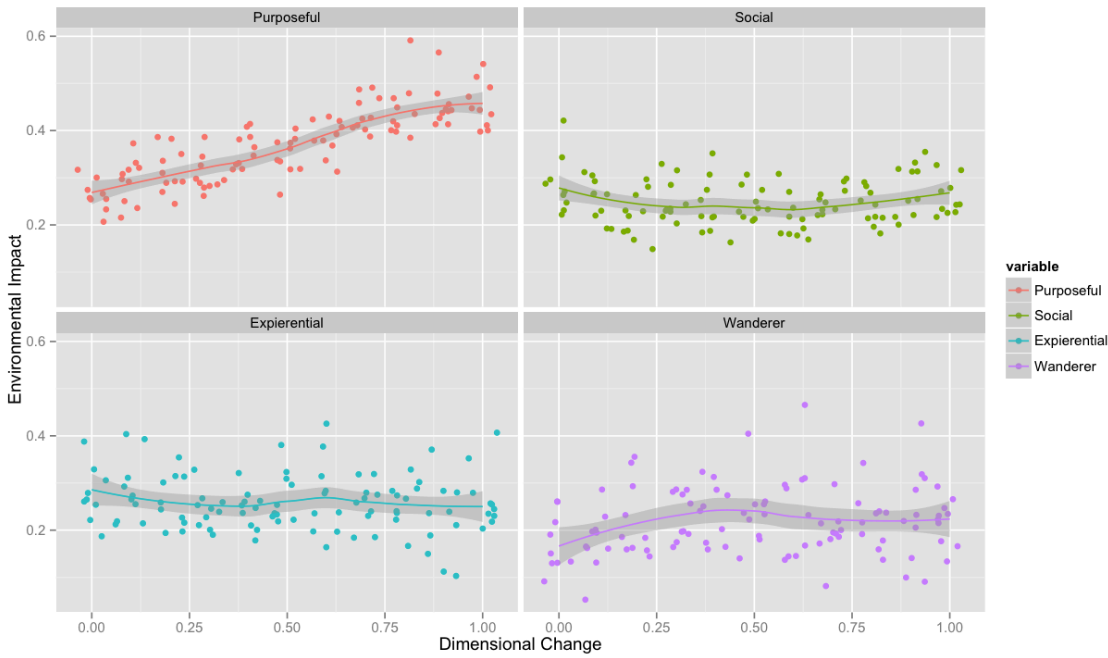


Figure 29 – Impacts of dimensional changes on different pedestrian types.

The category ‘public safety’ improvements include the variables safety, security, and emergency response. Safety and security indicate the speed and proximity of private automobiles on the road network, whereas emergency response refers to the interactions of emergency service vehicles with other entities in the network. The results from the model indicate that iterative changes to the safety of the environment has a small positive impact on *social walkers*, but has little to no effect on other types of pedestrian practices **(Figure 30)**.

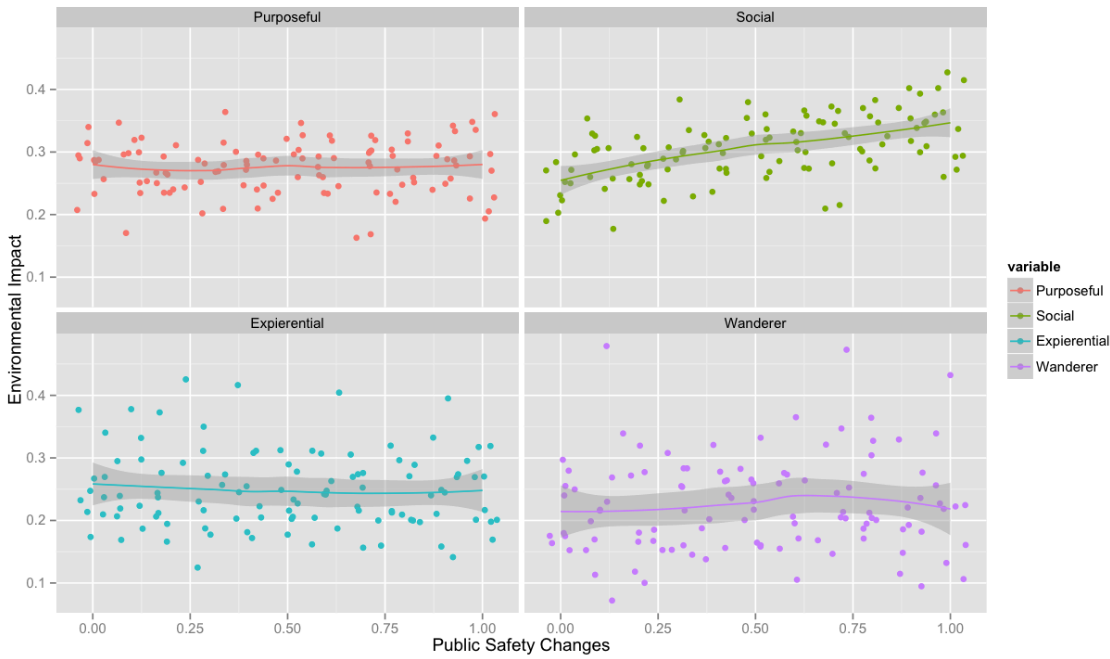


Figure 30 – Impacts of public safety changes on different pedestrian types.

The category ‘economic benefits’ includes the variables freight mobility, business vitality, fundability, asset management, and project benefits. These variables measure both the business related impacts as well as the financial burden on the city of redevelopment. The results from the model indicate that iterative changes to economic benefits, as measured by the official assessment, have little to no effect on any of the pedestrian types **(Figure 31)**.

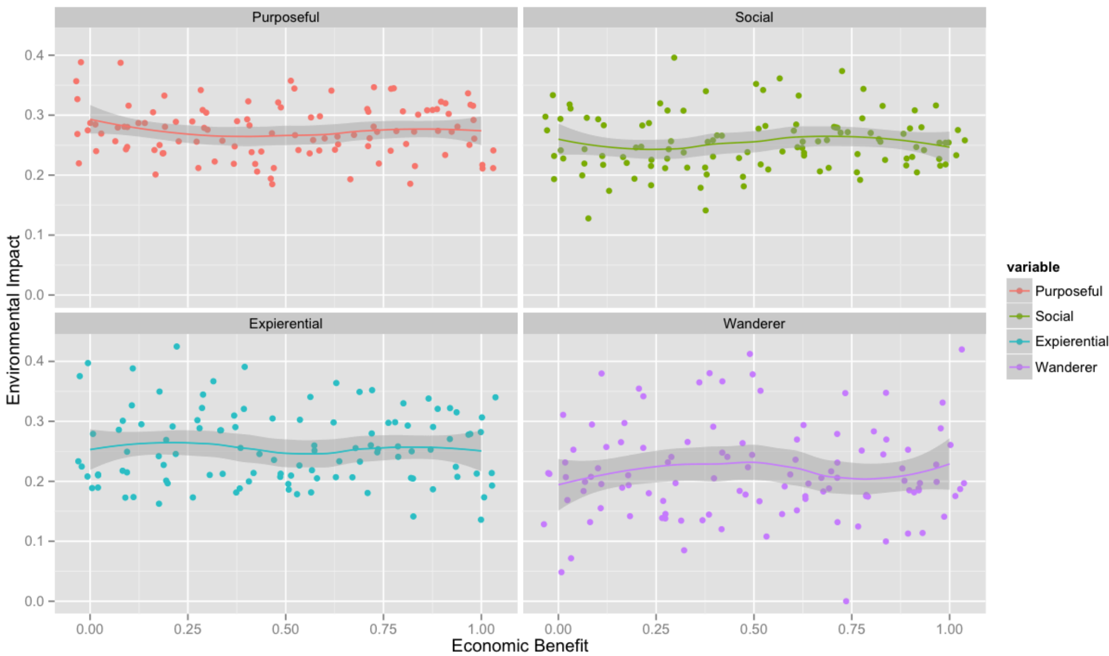


Figure 31 – Impacts of economic benefit changes on different pedestrian types.

The category 'community support' includes the variables equality, economic access, pedestrian facilities, bicycle facilities, transit facilities, and community vision. These variables measure the ways in which redevelopment supports community goals and provides facilities and access across a wide range of citizens and individual practices. The results from the model indicate that iterative changes to community support have a positive impact on *social walkers* and *experiential walkers,* a small positive impact on *purposeful walkers,* and little to no effect on *wanderer walkers* **(Figure 32)**.

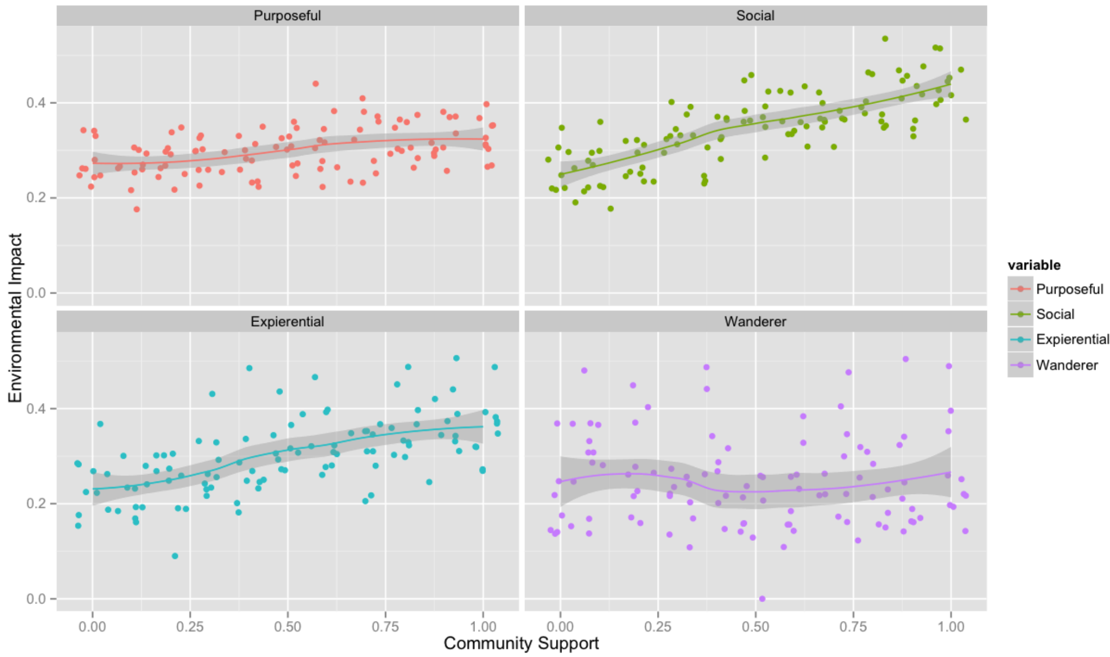


Figure 32 – Impacts of community support changes on different pedestrian types.

The analysis of this model most clearly reveals that the original assessment by the city of Eugene assumes all citizens will respond equally to changes, and the binary metrics used to evaluate the six conceptual alternatives in the official assessment misrepresents the impacts of each redevelopment variable on pedestrians. To correct this assumption, this paper uses a linear regression analysis between each redevelopment variable and each pedestrian type to create a weighting chart for a more detailed and refined assessment of the different conceptual alternatives **(Table 8)**.

Table 8 – Weighting table for all variables and pedestrian types.

	Purposeful	Social	Experiential	Wanderer
Dimensional	3.3215	-0.01435	-0.6428	0.6251
Safety	0.2590	3.4821	-0.3378	0.2984
Economic	-0.3202	0.3535	-0.1809	0.08159
Community	2.7184	3.1685	2.3398	-0.07749

The weighting table is combined with the formal assessment by the city of Eugene and the distribution of people from the principal component analysis of pedestrian types to evaluate the impact of each redevelopment on a heterogeneous population of pedestrian citizens. With this approach, the impact of each conceptual alternative is measured in human-centered terms, giving considerably more attention to the range of pedestrian practices and being inclusive of individual differences within the population **(Table 9)**.

Table 9 – Human-centered assessment of alternative redevelopment concepts. Green indicates dimensional variables, yellow public improvement safety variables, blue economic benefit variables, and pink community support variables.

Alternative		1	2	3	4	5	6
Access and Mobility	Neighborhood connectivity			1.77	1.77		1.77
	Motor vehicle travel time			-1.87	-1.87	-1.87	-1.87
	Active mode travel time			1.77	1.77		1.77
Safety and Health	Safety			0.85	0.85	0.85	0.85
	Security			0.85	0.85	0.85	0.85
	Emergency response			-0.56	-0.56	-0.56	-0.56
Social Equity	Equity			2.61	2.61	2.61	2.61
	Economic access			2.61	2.61	2.61	2.61
Economic Benefit	Freight mobility			-0.24	-0.24	-0.24	-0.24
	Walkable/bikeable			1.77	1.77	1.77	1.77
	Business vitality		0.31				-0.24
Cost Effectiveness	Fundability	0.31			-0.24	-0.24	-0.24
	Asset management	0.31	0.31	0.31	0.31	0.31	0.31
	Project benefits	0.31	0.31	0.31	0.31	0.31	0.31
Climate and Energy	Pedestrian facilities				-0.36	2.61	
	Bicycle facilities			2.61	2.61		2.61
	Transit facilities					2.61	
Community Context	Community vision				-0.36	2.61	
Total		**0.93**	**0.93**	**12.79**	**11.81**	**14.23**	**12.29**
Eugene Assessment		**3**	**3**	**7**	**4**	**6**	**5**
Difference		**-2.07**	**-2.07**	**5.79**	**7.81**	**8.23**	**7.29**

The results of the model find two important considerations not calculated in the official assessment of South Willamette Street. First, not all variables are equal when considering the range of pedestrian practices within the redevelopment space; the variables of community support and dimensional changes have a much more significant influence on pedestrians in the system than the variables of public safety and economic benefit. The model analysis also reveals that in the redevelopment of pedestrian spaces, design practices focusing on network connectivity, non-automobile facilities, and inclusive or evenly distributed development are essential changes. Often the issues of public safety and business vitality are linked together and serve as the main focus of discussion, both in arguments supporting and opposing larger redevelopment projects. The analysis shows arguments within this framing likely fail to capture the actual impacts on pedestrian movement within redevelopment spaces **(Figure 33)**.

Figure 33 – Example of economic benefit and public safety being linked in opposition to redevelopment. Photo by Author.

Additionally, the new assessment illustrates the impact of each conceptual alternative on pedestrians are not even across all types of walkers, and assumptions of homogenous or uniform impacts from the identified redevelopment variables neglects many of the individual and human-centered elements of pedestrian practices. The results from the official assessment of the conceptual alternatives ranked option three highest, and the redevelopment of South Willamette Street to meet these specifications is set to begin in Summer 2016. While there are multiple variables and modes of transportation to consider when evaluating the redevelopment of South Willamette Street as a whole, the results from this analysis ranks option five as the highest **(Figure 34)**.

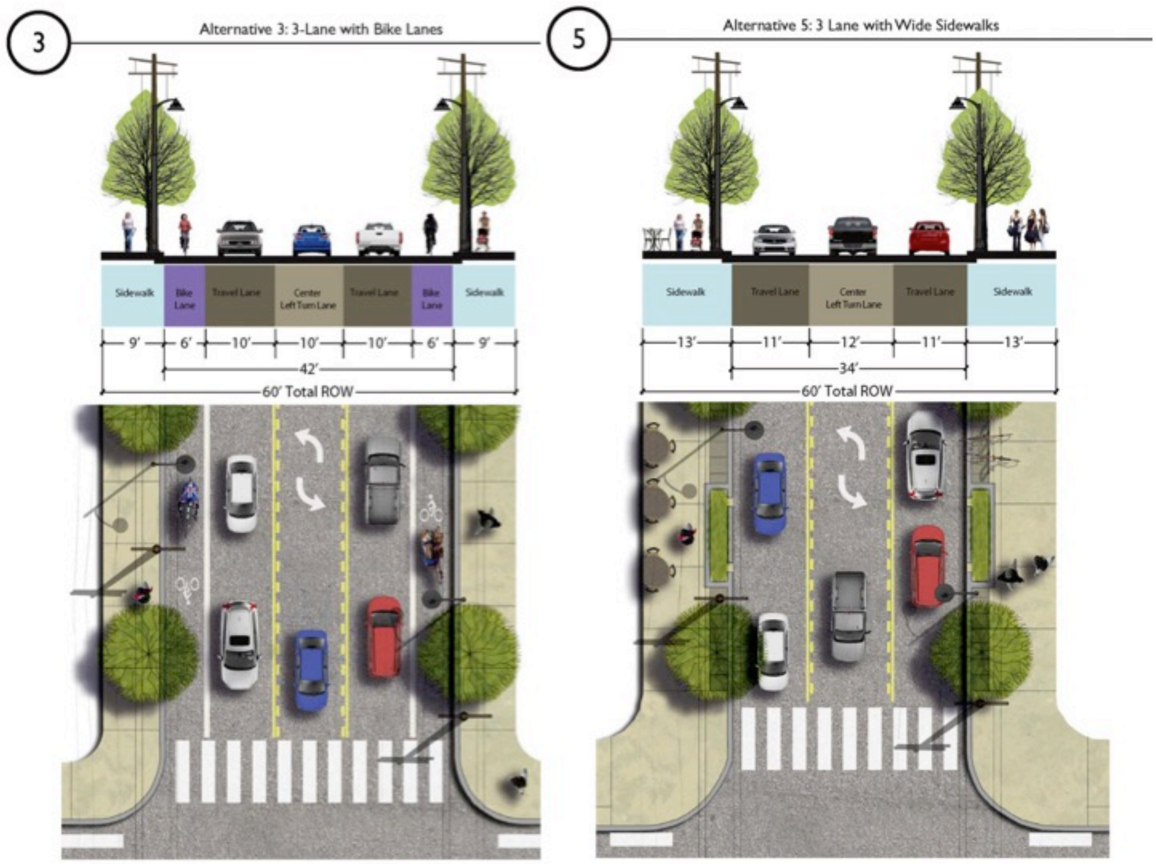


Figure 34 – Side by side comparison of alternative concept three and five for the redevelopment of South Willamette Street. Source: City of Eugene 2014.

This analysis does not suggest option five is superior to option three, nor is it meant to predict how a broader sense of walkability will change from these different structural arrangements. Rather, the analysis of the PAR model shows the strengths and weaknesses of the alternative concepts in a more nuanced and thoughtful way, disrupting assumptions about the impact of different environmental variables on a representative population of individual pedestrians and providing clues pertaining to the most important variables to consider when designing pedestrian-friendly spaces in multimodal corridors. While options three and five appear quite similar, small differences between the two provide clues into features most desirable to pedestrians.

First, the sidewalk dimensions of option five create more space for multiple types of pedestrian practices and accommodate features such as sidewalk furniture, public art, and social spaces. Option five also provides more room in the road network, creating more space for cars to operate. Option three does have bike lanes where five does not, creating both a buffer for pedestrians and access for another mode of transportation. Both alternatives illustrate the difficulties in supporting multiple modes of transportation within 60 feet of right of way, and regardless of the configuration certain modes will be privileged while others disadvantaged. The PAR model serves to remind us how a human-centered evaluation of such projects provides can highlight specific features that are pedestrian friendly and illustrate how the range of pedestrian experiences respond to different environmental features.

Frameworks for Supporting Transportation Planning

Heterogeneous Agent Representations

As the PAR model and the subsequent analysis show, agent-based models can provide unique and valuable insight into transportation planning issues, especially when there is a need to represent model entities as heterogeneous decision-making individuals. Before making the claim that agent-based models are an appropriate method for transportation planning issues, it is critical to explore in more depth the types of questions that need to be asked before implementing an agent-based model and to discuss how to best frame the knowledge produced by model results to support planning practices.

Agent-based models provide a new theoretical approach in which to explore complex human-environmental relationships. As Miller and Page (2007) explain, "(t)ools like agent-based object models allow us to create new theoretical ponds that can harbor simple, yet thriving, social ecosystems" (78). As is the case with many new tools, there are significant epistemological and communication challenges that must be considered when using agent-based models to evaluate the potential impacts of a policy or planning decision. Batty and Torrens (2005) acknowledge the difficulty in explaining and communicating results of agent-based models, illustrating how flexible and heterogeneous representations of individuals can clash with public notions of science and specifically concepts of quantifications, forecasting, and validation common in traditional models. O'Sullivan and Perry (2013) argue agent-based models should not be seen as predictive analytical tools, but rather as abstract representations of the world where the interactions of multiple individuals may reveal unexpected patterns.

In the PAR model analysis, the results indicate a pattern of pedestrian interactions with different structural elements of the material environment, which varies based on the pedestrian type classifications (**Figure 35**). As mentioned, the pedestrian type classification is based on the scores of psychometric test across multiple cognitive measures. The test scores should not be confused with identifying a consistent typology – i.e. performance on a given test indicates a certain set of pedestrian behaviors consistent across time and space. Rather, participant performance on the test results in a distribution of pedestrian types, which can be used to populate the model environment in a representationally realistic way. Coding a set of realistic agents allows for an analysis of the range of impacts different types of changes to the environment may have on a population of citizens. This should not be confused with assumptions that the model can predict with certainty direct impacts of the different conceptual alternatives on individual or groups of pedestrians.

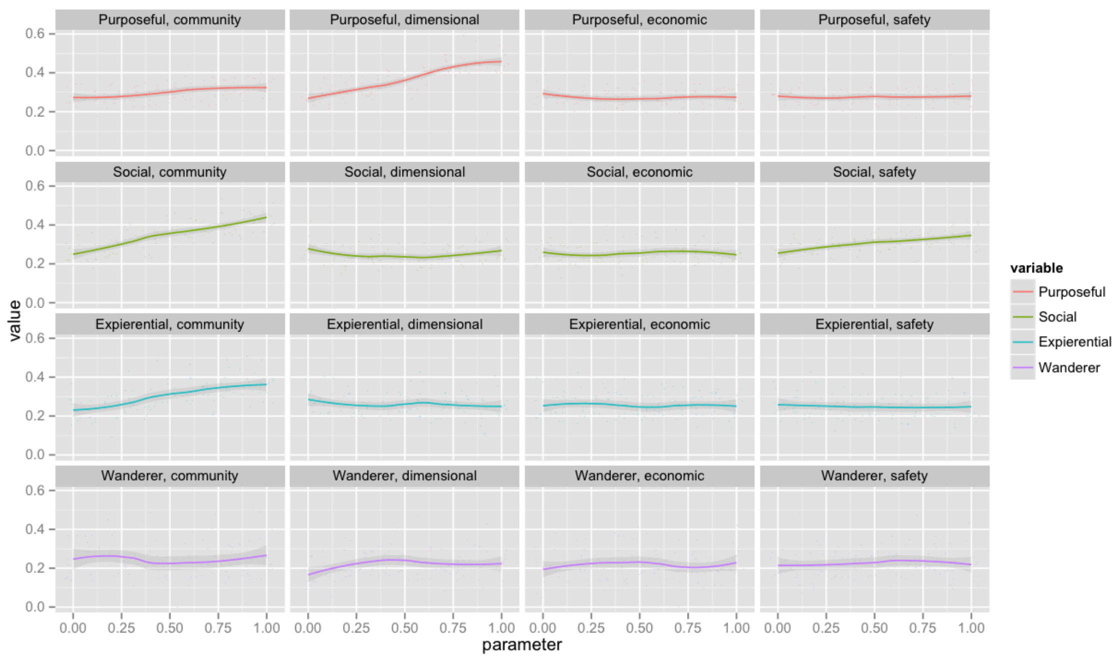


Figure 35 – Impact of different redevelopment variables across all pedestrian types.

Considerations for Agent-Based Models

A number of factors need to be considered before designing an agent-based model for any research problem, especially in value-laden municipal projects with public impacts and numerous political actors. The table below (**Table 10**) illustrates some of questions, research goals, and behaviors that will benefit from an agent-based modeling framework versus traditional statistical models in support of planning practices.

Table 10 – Comparison of traditional statistical model and agent-based models across eight different categories to aid in method selection, expansion of framework proposed by Miller and Page (2007).

	Traditional Model	**Agent-Based Model**
Model Purpose	Predictive	Generative
Knowledge Produced	Outcome-based	Process-based
Representation Criteria	Precise	Flexible
Modeling Approach	Top-Down	Bottom-Up
Model Behavior	Static	Dynamic
Model Entities	Homogenous	Heterogeneous
Entity Motivations	Optimizing	Adaptive
Epistemology/Philosophical Approach	Reductionist	Phenomenological

The first step in deciding whether or not to use an agent-based model is to link the research question to the desired knowledge needed to answer a specific question. At a basic level, the choice of whether or not to use an agent-based model depends on the epistemological or philosophical assumptions underpinning the research questions. If the question is one that takes a high amount of precision to forecast or predict a specific outcome based on the relationship of two or more variables consistent over space and time, and/or if the system in study can be reduced to a minimal number of relevant parts, a more traditional statistical modeling approach is likely the most suitable. If the question, however, is one that is best answered through a deeper understanding of the adaptive and decision-making processes of heterogeneous individuals, and/or if there are variables typically regarded as subjective such as perceptions, memories, cognition, and emotions that are driving the decision-making of individuals within a system, an agent-based modeling approach is likely the most appropriate method. Prior to the decision of whether or not to design and implement an agent-based model, there needs to be careful and deliberate consideration in negotiating the philosophical roots of the question and the desired type of answers before moving forward with a particular methodology. Without such deliberation, we may find ourselves in a recursive loop of questions, methods, and results that fail to align or produce meaningful results.

Once an agent-based model has been designed and implemented, the results need to be communicated in a way to support, rather than confuse, planning practices. Models are abstract representations of phenomena, and agent-based simulations typically illustrate process-oriented details rather than predictive capabilities. Municipal redevelopment projects often rely on multi-actor approaches to decision-making and knowledge production in the creation of new policy (Frame 2008). And while agent-based models do produce uniquely different types of knowledge about urban systems, especially in comparison to conventional geospatial and geostatitical applications (Sheppard 2005), process-oriented results often disrupt established political discourse coalitions and can cause confusion among local actors and decision-makers rather than provide a clear path forward.

Given the difficulties in communicating dynamic processes rather than statistically significant predictions, coupled with the political implications of scientific uncertainty (Funtowicz and Ravetz 1993), many have recommended specific methods to communicate the modeling process. Grimm et al. (2010) advocate using a formal protocol to convey model variables, event scheduling, and design decisions, as detailed in the model design section of this paper. Other recommendations include the use of open collaboration platforms for participatory design (Crooks et al. 2008), treating models as cartographic or visual products (Miller and Page 2007), and the reframing of process-oriented models as geographical narratives describing the behaviors of a single agent as a way to explain the steps that produce whole-system patterns (Millington et al. 2011).

If we think of models as a way to produce knowledge about systems, we can conceptualize traditional statistical and forecasting models as capable of producing knowledge with relatively low uncertainty about a rather narrow range of outcomes. In this case, historical data and observations serve as inputs to inform model design aiming to understand the relationships between and the predictive power of variables, outlining a range of possible outputs or solutions with as little uncertainty as possible. Agent-based models, on the other hand, produce knowledge across a wide range of possibilities, exploring gradients within a spectrum of possible results, with little predictive capability. Instead, an agent-based model informs on the processes that produce observable patterns, and illustrates how changes to initial conditions, interactions between entities, and adaptive processes could scale up to impact system-wide outcomes. Within a public planning forum, the question of whether or not to use an agent-based model hinges on the philosophical underpinnings of the research questions, the assumptions of the modeler, the amount of existing data about the system, and the range of acceptable uncertainty in results. While agent-based models often provide more unique and dynamic approaches to evaluate serious and sometimes hard-to-define transportation planning issues, the decision of whether to base planning decisions and policy on agent-based modeling outputs should be made with a degree of caution.

The analysis of the PAR model illustrates the interactions and relationships between design variables and different types of pedestrian practices. In doing so, much can be learned about the individual differences in human pedestrian behaviors as well as how different types of design features impact specific types of movement. More importantly, however, the PAR model provides a new metric in which to evaluate alternative design concepts in planning, disrupting assumptions that simple tabulations of uniformly assessed variables provide an accurate and complete evaluation of potential changes to the environment. While the PAR model highlights these two important findings, it is not able, nor is it intended to, clearly define which of the six alternative concepts is most appropriate in the redevelopment of South Willamette Street.

Conclusion

Literatures on the everyday experiences of walking in the city (see e.g. Lynch 1960; Jacobs 1961; Whyte 1988; Solnit 2000) all place a heavy emphasis on the more subjective variables in understanding pedestrian practices. Many existing pedestrian models are embedded with reductive ontologies (O'Sullivan and Hakley 2000), framing the pedestrian as a rational transportation unit optimizing resources or reacting to other agents across the model environment. While wayfinding and evacuation approaches to pedestrian movement have proven effective for discrete purpose or event-based phenomena, other aspects of pedestrian movement such as communication with other agents, cognition and emotion, uneven internal representation of perceived spaces, and multiple agent motivations need to be incorporated into the agent-based framework to understand more everyday human pedestrian behaviors.

Despite the communication barriers embedded in process-driven analysis, agent-based modeling remains a powerful and innovative way to understand the relationships between changing spaces and individual behaviors, serving to highlight many unexpected facets of both individuals and the system in which they are embedded. The PAR model described in this paper incorporates a data-driven representation of cognition into agents as a way to explore the implications of different types of redevelopment and design on realistic pedestrian types. The results indicate the design variables of dimensional changes and community support has a stronger influence on a heterogeneous population of pedestrians than the design variables of public safety and economic benefits classifications. The model also introduces a weighted interaction scheme highlighting flaws in the official assessment administered by the city of Eugene. In doing so, the PAR model provides insight that would be hard or impossible to obtain with traditional statistical models.

Due to the immense potential of agent-based models to shed light on pressing issues in land-use, urban growth, and especially transportation planning practices, it is critically important that research on agent-based models, both from modelers and from planners, continues to focus not only on design and evaluation metrics, but on the discursive dimensions of the knowledge produced by models and the role of that knowledge in policy debates. This is especially true for pedestrian modeling applications, as pedestrian-oriented development has great potential to radically transform urban transportation spaces and examine pressing global issues with localized sustainable practices. In the context of increasingly urgent social and environmental issues, there is a pressing need to understand how people move through everyday spaces, how various human subjectivities play into pedestrian decision-making, and how to best design and communicate model results to support municipal planning and development.

Agent-based models provide a relatively new scientific tool to integrate human-centered and configurational approaches to urban and transportation planning. A computational approach to represent human-centered and everyday pedestrian behaviors has significant methodological contributions in the field of planning and elicits strong insight to address many community-based goals of livability, safety, and environmental sustainability. Thoughtful pedestrian representations in agent-based models aligns with emerging municipal goals of data-driven smart city design initiatives (Townsend 2013), while drawing linkages between individual representations of space and the concrete elements of the city, informing a deeper understanding of pedestrian behaviors and transportation choices. Additionally, an agent-based modeling approach allows for different design variables, infrastructure configurations, and social conditions to be systematically simulated in a model environment, fostering a broader understanding of how real-world behaviors are influenced by a variety of material and immaterial changes in the environment. While there are still many issues in design protocols, validation techniques, and communication frameworks that require continued attention, agent-based modeling can serve as a powerful and low-cost computational platform to learn about urban and transportation systems in supporting planning practices.

CHAPTER V
CONCLUSION

Practices of walking vary greatly from individual to individual, and are often at odds with dominant discourses in urban and transportation planning. As cities continue to consider, propose, and financially invest in pedestrian-oriented design as a way to examine serious issues ranging from the local to the global scale, deepening understandings of the human dimensions of walking will become increasingly important to broader understanding how changes to the material environment actually impact people and daily walking practices. The three chapters of this dissertation give considerably more attention to the human elements of walking by developing a set of new theoretical, methodological, and practical frameworks for advancing representations of the pedestrian in the urban space and within a larger transportation system.

In untangling the structural and human-centered dimensions of pedestrian movement outlined in the previous chapters, this dissertation provides theoretical and empirical work to illustrate how human dimensions of walking can be incorporated into both computational modeling as well as more broadly into policy-centered transportation discourses. The work presented is particularly focused on developing theoretical frameworks, human-subject methodologies, computational models, and validation techniques to understand how individual cognitive capabilities during spatial movement can inform a more human-centered approach to transportation planning. The findings from the three chapters answer the four overarching research questions guiding the project as a whole.

Chapter 2, “Pedestrianism and the more-than-rational agent” addresses the philosophical roots of the rational agent representation by tracing the *homo economicus* social model to tenets of neoclassical economics, detailing how the rational agent is embedded with utilitarian and optimizing transportation behaviors reliant on the concepts of cost/benefit analysis and global knowledge of all possibilities. The framing of individual pedestrians as rational agents produces a framing of the environment that relies on configurational spatial ontologies, fixed environmental affordances, and hard urban materiality. This chapter illustrates how orthodox urban and transportation planning practices often employ this coupled framing of individual agency and spatial structure, which, in turn, essentially renders the pedestrian as a slower moving version of the private automobile within a system of fixed, immutable infrastructure. The chapter continues by detailing how framings of the rational agent and configurational environment influence transportation policy, illustrating how changes to street infrastructure often rely heavily on dimensional and material changes under the assumption these aspects afford a set of predictable and generalizable behavior from a group of citizen pedestrians.

In response to these assumptions, this paper introduces a framework for a more-than-rational agent, a formal representation that makes room for pedestrian agents to perceive and behave in a manner that is not reducible to the form of the environment and not consistently utilitarian across time and space. The more-than-rational agent embodies emotional, cognitive, and habitual characteristics, allowing for softer encounters and performative engagements in the urban environment and specifically in the transportation network. In contrast to the geometric or configurational spaces of the rational agent, the more-than-rational agent relies on topological assessments of the environment that allow for fragmented, asymmetrical, and uneven internal spatial representations. The more-than rational agent framework serves as an alternative formal representation for increasingly data-driven and gridded urban analytics, giving agency and life to pedestrians typically viewed as inert, mechanistic, and predictably rational in structural models. Expanding representations of the human pedestrian to a more-than-rational framework enables deeper and more meaningful engagements with how people move through and experience urban spaces.

Chapter 3, "Ecological validity of human representations in agent-based models" presents a methodological approach to advance the representation of human pedestrians in computational models and investigates the research questions of how can data generated about individual differences in environmental cognition be used in the development of a pedestrian movement model. This paper details the development of a data-driven empirical agent-based modeling approach to represent human cognition during pedestrian movement. The method for doing so encodes agent representations within an abstract model environment with a high level of cognitive capabilities, which are derived from measuring task completion performances across 42 participants on a variety of psychometric test. Cognitive representations and agent behavior are validated using an ecological validation approach that triangulates within subject data points from psychometric test, in-field behavioral measures, and model outputs to determine the credibility of the model in representing a range of everyday pedestrian behaviors. The results illustrate high confidence in three important relationships: the ecological consistency of the psychometric data used to code agent cognition, the reliability of the model parameterization in representing the phenomenon of individual pedestrian practices, and the ecological validity of the agent behaviors in mirroring real-world pedestrian behaviors.

The importance of developing deeper representations of cognition in agent-based modeling, particularly in pedestrian and human movement models, extends beyond expanding theoretical approaches to represent human pedestrians. First, this method positions individual human-subject data as the basis for designing and evaluating the model, relying on small and soft datasets that specifically measure individual processes and differences. This approach turns attention to the individual and, rather than attempt to make generalizable claims based on aggregate population data, instead focuses on how to capture the full spectrum of abilities and performances across multiple ecologically consistent internal variables. Moving from generalizable to individual representations requires engagements with a deeper sense of cognition than is commonly employed in pedestrian models, and as the chapter suggest, results in a more meaningful and human-centered coding of computational agents.

Finally, by understanding specifically the links between cognitive processes and pedestrian practices, this paper provides an innovative approach to understand human processes often overlooked in conventional transportation planning and design practices, illustrating how the development of agent cognition aids in the credibility of real-world pedestrian model. A human-centered approach to transportation design fuels the creation of spaces and systems that favor inclusion of a wide range of practices, and may potentially resonate with a greater number of individual pedestrians within a system. The development of dynamic cognitive representations links human and artificial agents, providing a foundation to further the design of individually intelligent, decision-making pedestrian agents for dynamic urban and transportation redevelopment simulations. Finally, identifying and explicitly modeling cognitive variables deepen human representations in computational agent-based pedestrian models, providing greater theoretical credibility and practical applicability to models depicting how pedestrians perceive, interact, and behave in urban spaces. This is especially important as practices of walking are embodied human activities, and in large part driven by cognitive, experiential, and social processes. Linking the observable patterns of human movement to internal and individual human processes is imperative, as greater understandings of human agency during pedestrian practices can have significant influences on both design practices and on the focus of analytical approaches conceptualizing human movement in transportation redevelopment projects.

Chapter 4, "Agent based models in supporting pedestrian transportation planning and design," discusses an applied modeling application to evaluate a transportation redevelopment project in Eugene, Oregon to examine the question of what key design variables in transportation redevelopment projects emerge from a cognitive pedestrian movement models. This chapter introduces a redevelopment project on South Willamette Street in Eugene, illustrating the complexities of the planning process, the range of conceptual alternative for redeveloping transportation infrastructure along this corridor, and the environmental variables in the official city assessment of alternative concepts. By extending the cognitive model developed in the previous chapter to a real-world transportation redevelopment project, the model produces results indicating the design variables of dimensional change and community support have a stronger influence on a heterogeneous population of pedestrians than the design variables of public safety and economic benefits classifications. This analysis clearly demonstrates that all the variables used in the official assessment of the project are not equal. Specifically, the model analysis shows that in the redevelopment of pedestrian spaces, design practices focusing on network connectivity, non-automobile facilities, and inclusive or evenly distributed development are essential to encourage pedestrian mobility and need to be given extended consideration in the redevelopment of multimodal transportation spaces that are inclusive to all modes of transportation.

This chapter concludes with a reflective assessment on the role of agent-based models in supporting planning practices. As a relatively new computational approach to representing and analyzing spatial systems and processes, agent-based models have high potential for helping planners answer some of the wicked questions surrounding the transportation system. This reflection argues that agent-based models with human-centered representations of pedestrian can have significant contributions by drawing linkages between individual representations of space and the concrete elements of the city, informing a deeper understanding of pedestrian behaviors and transportation choices. Additionally, an agent-based modeling approach allows for different design variables, infrastructure configurations, and social conditions to be systematically simulated in a model environment, fostering a broader understanding of how real-world behaviors are influenced by a variety of material and immaterial changes in the environment. This reflection also cautions that while agent-based models can provide a unique looks at the transportation system, there are still many issues in design protocols, validation techniques, and communication frameworks that require extra attention, especially in value-laden public policy discussions.

The three chapters presented in this dissertation outline an alternative, human-centered approach to the representation of the pedestrian, providing theoretical, methodological, and practical solutions to conceptualize how soft variables such as emotion, motivation, and especially cognition influence the practices of walking. Walking is a mode of transportation that offers numerous benefits to both the individual and the community, a form of movement that addresses issues ranging from individual health to climate change, simultaneously supporting personal solitude and freedom and enhancing community social value. Modernist approaches to urban transportation systems overwhelmingly favor and orient design towards the private automobile, consequently constructing an environment where pedestrian spaces are either uncertain and unappealing or sanitized and commodified. In constructing strategies about ways to incorporate the pedestrian into a larger transportation system and as a vital aspect of urban life, we need to give considerably more attention to the human aspects of walking, including cognitive and soft processes, emotional and experiential practices, more-than-rational and performative motivations, and habitual and slow mobilities. Walking is in fact one of the most basic human expressions, one demanding considerably more attention to in the fields of geography and planning.

"Walking is the great adventure, the first meditation, a practice of heartiness and soul primary to humankind. Walking is the exact balance between spirit and humility."
– Gary Snyder, 1990

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