From Observation to Prediction: The Trajectory of Movement Research in GIScience

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Abstract: Movement is a key to understanding the underlying mechanisms of dynamic processes. Over the past two decades, the availability of an unprecedented amount of movement observations at fine spatial and temporal granularities has resulted in substantial advances in different areas of movement research in GIScience and other related disciplines. This article describes a continuum encapsulating essential elements of movement research. The study of movement involves development of concepts and methods to transform movement observations to knowledge of the behavior of moving phenomena under known conditions. This knowledge is then used to calibrate simulation models to predict movement and behavioral responses in varying environmental conditions. The article highlights significant achievements, existing gaps, and potential future directions of the trajectory of movement research across this continuum in GIScience.

Keywords: Movement analysis, movement, behavior, movement observations, environment, geographic context, trajectory analysis, movement research.

1 Introduction

Movement is essential to almost all organisms and spatiotemporal processes. Movement as "a *change* in the spatial location of the whole individual in time" [37, p.19052] results from complex states and behaviors of moving entities. Movement occurs in *space* and *time* across multiple scales and through an embedding *context* which influences how entities move. The importance of spatiotemporal aspect of movement has attracted a wide range of studies in Geographic Information Science (GIScience).

Movement research is important in many areas of science and technology, such as movement ecology, environmental studies, behavioral studies, epidemiology, and

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transportation, to name but a few [17]. Movement ecology aims at understanding local movement and global migration patterns of animals and their space utilization patterns [23, 13]. Trajectory analysis plays a key role in behavioral and social sciences, urban and transportation planning to study human mobility and activity pat- terns [21, 45, 39, 46]. Movement analysis is essential in public health and epidemiology to model disease spread in space and time, and estimate human exposure to pollution or infectious diseases [43, 20, 33]. The advent of inexpensive and ubiquitous positioning technologies has triggered a wealth of interdisciplinary research collaborations among developers of methods and domain experts. Demšar *et al.* [11] provides a comprehensive review of recent developments in movement analysis and visualization methodologies resulting from such collaborations between ecologists and experts from GIScience.

Over the past two decades, the study of movement has gained significant momentum in GIScience [28, 32, 29]. Although movement research crosses many disciplinary boundaries (e.g. movement ecology, behavioral studies, transportation, information science, human health), this article mainly focuses on the trajectory of movement research in *GIScience*. The main contribution of this article is the introduction of a new and overarching framework to illustrate the continuum of research that enables us to understand movement and its underlying processes. For each element, the article portrays the strengths and existing gaps in the current state of research, and provides some suggestions as where the research should be heading in the future. One of the key suggestions is that the field should be heading more towards the development of informed models to predict the future behavioral responses of spatiotemporal phenomena to environmental changes.

The remainder of this article is organized as follows: Section 2 introduces a continuum encapsulating the key elements of movement research. Section 3 describes the components of movement and their associations to one another. Section 4 discusses GIScience methods for *understanding movement*. Section 5 reviews *simulation and predictive models* for movement, which have received less attention in the past from the community. Section 6 summarizes the natural progression of movement research over the past twenty years, and discusses a proposal for future directions of the research and issues that need to be taken into considerations.

2 Movement Research Continuum

Figure 1 illustrates a continuum encapsulating fundamental areas of movement research, which are tightly linked to one another. Study of movement entails two inter-connected strands of research for (1) *understanding movement processes* (the right side of Figure 1); and (2) *modeling* behavior of moving phenomena and *prediction* of their responses to environmental changes (the left side of Figure 1). These two processes are tightly connected and feed into each other, often through a *validation* procedure on the basis of real *movement observations*.

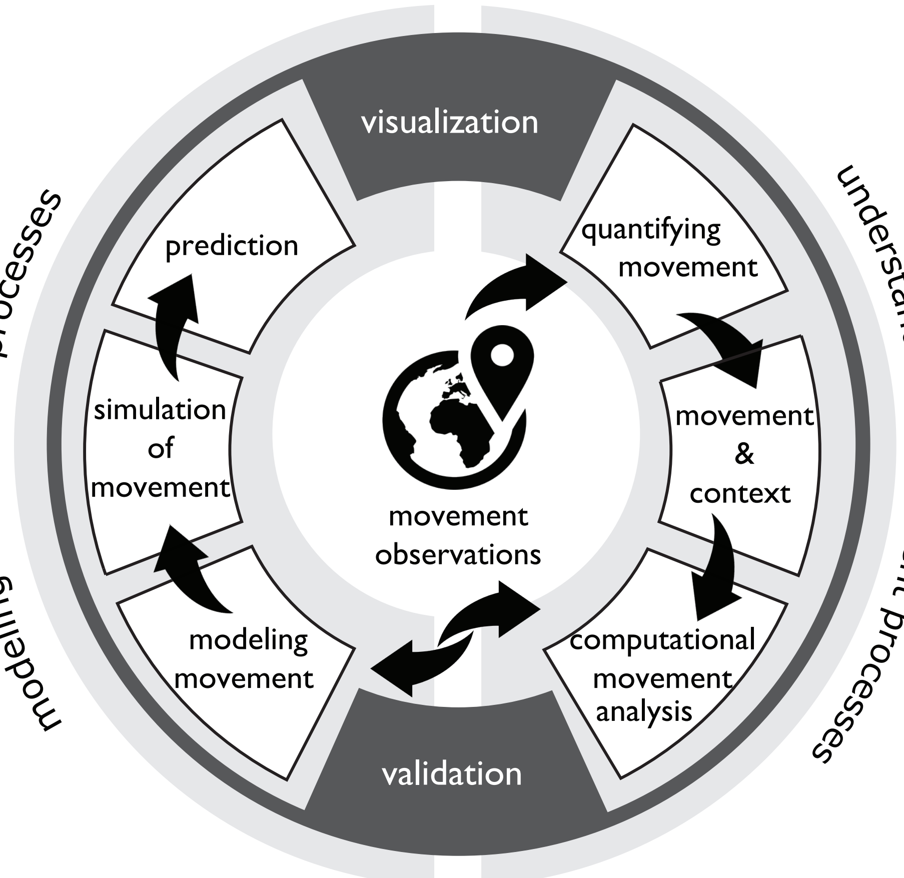

Figure 1: Movement research continuum

At its core, the continuum is supported by raw *movement observations*. Movement observations are often obtained through tracking real-world moving entities using satellite positioning, video tracking, or others sensor technologies (e.g. GPS, Argos, RFID tags, Geotags, Bluetooth). The continuum relies on *visualization* techniques for exploration of observations and communication of results, and on *validation* to ensure reliability of methods, models, and discovered patterns. Movement observations feed into analytical methods to *quantify movement* tracks, movement parameters and patterns, and their relationships to the *context* within which the movement is embedded. This information is transformed into knowledge of movement through "*computational movement analysis*" [29], (e.g. using movement pattern mining and machine learning). This facilitates the development of *movement models*, which can increase our understanding of the behavior of moving phenomena. The resulting knowledge are then used to *validate and calibrate models* to translate behavior of dynamic phenomena into *informed movement simulations*. Ultimately, the whole process feeds into the development of *predictive models* to capture behavioral responses and movement of dynamic phenomena through space and time and in varying environmental conditions. These models can be *parameterized* and *validated* using real *movement observations*.

In GIScience, the study of movement was initiated with quantifying trajectories, movement parameters and patterns through the development of computational geometry and movement analysis approaches [25, 22, 32]. Movement research has since progressed with the design of analytical and visualization methods to transform raw observations to knowledge of the behavior of moving phenomena [35, 38, 11]. This article provides a summary of the progress of movement research in GIScience along this trajectory by highlighting significant achievements made over the past twenty years on different elements of the continuum. For a comprehensive review of the state of research, the readers are advised to refer to recent survey articles [32, 38, 29, 11].

3 Components of Movement

According to the movement ecology paradigm proposed by Nathan *et al.* [37], movement consists of several components and different processes that connect these components to one another. Figure 2 presents an adapted version of the movement ecology paradigm with some modifications to account for a broader range of moving phenomena applied to different domains of GIScience (e.g. behavioral studies, environmental studies, ecological studies, transportation).

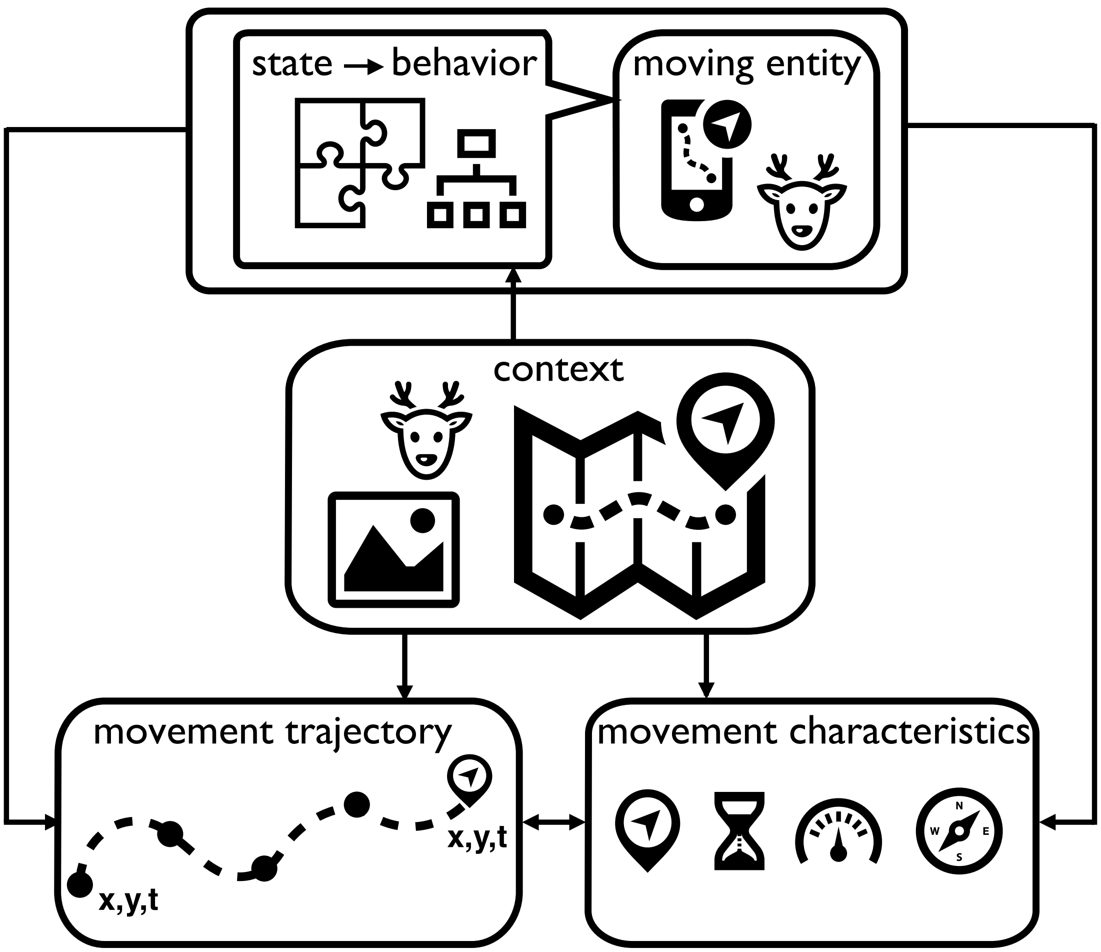

Figure 2: Components of movement

Movement is a process that occurs as a response to the *state* of a *moving entity* across multiple *spatial* and *temporal* scales. Moving entities are individuals (e.g. vehicles, humans, animals) or phenomena (e.g. hurricanes, wildfires, oil spills) whose position changes over time. The *state* of an entity either emerges from *intrinsic* properties of the individual (e.g. being hungry or readiness to move) or is influenced by the *context* (i.e. presence of a pray or predator for animals, daily schedule for humans, rise in sea surface temperature for development of hurricanes). The *context* includes influencing external factors such as the geography and physiography in which the movement takes place, environment and ambient attributes, transportation network, and presence of other moving agents in the vicinity. The entity's *state* leads to a *behavior* (e.g. hunting, patrolling, going to work, hurricane intensification). The *state* and resulting *behavior* determine the *characteristics* and *capacities* of movement (e.g. speeds, directions, accelerations, path sinuosity), which are highly influenced by *context*. Accordingly, the trajectory of a movement (i.e. a spatiotemporal path that is composed of a time-ordered sequence of coordinates) is driven by *behavior* and *context*. When more than one entity is involved in the process, their collective movements are driven by the interactions between the entities and their dynamics [19]. This collective behavior is also influenced by other contextual parameters in space and time.

4 Understanding Movement Processes

Movement observations are signals of real-world moving entities. These signals carry important information pertaining to *behavior* of these entities. To gain insights into movement processes it is necessary to develop methods to analyze these signals, identify *patterns* (i.e. regularities and structure) in movement datasets, and assess how they are influenced by their environment [12]. These insights then contribute to modeling, simulation, and ultimately prediction of movement (see Figure 1).

4.1 Quantifying Movement

The availability of fine resolution movement observations has facilitated GIScience with the development of effective methods to quantify the geometric properties of movement trajectories, their derivatives (e.g. speeds, acceleration, path sinuosity), and associated movement patterns [12]. These methods enable us to gain an understanding of the fundamental elements of movement and its patterns. This is indispensable as a basis for the development of computational and analytic techniques to extract knowledge from movement observations [17]. In many applications, studying *movement characteristics* of entities is more relevant than simply the geometry of their movement paths, as they convey the physical and biological notions of movement [16]. This information leads to insight into the semantics of trajectories, underlying mechanisms of movement, and the behavior of organisms.

4.2 Movement and Context

Movement is often driven by the characteristics of its embedding spatiotemporal *context*; the surrounding environment and the the nature of space (i.e. geographic and physiography) that the object is moving through. This includes external factors that influence a dynamic process at a specific time scale (moment or duration). Context can be characterized into different types such as networks (e.g. roads), obstacles (e.g. lakes, rivers), and landscapes, (e.g. land cover, vegetation, terrain), ambient attributes (e.g. weather conditions), and presence of other agents (e.g. interactions) [6]. These parameters can trigger a specific behavior (e.g. hunting, patrolling, walking, biking) and hence they can enable or limit movement as a consequence of that behavior. For instance, a tiger patrols a soft boundary of its home range more often than a boundary with rigorous terrain characteristics [2]. Therefore, movement observations alone cannot describe all mechanisms behind movement processes. In order to correctly identify patterns and their causes, and understand behaviors of moving phenomena it is essential to relate movement to its physical environment.

Context has been an important part of GIScience studies which have dealt with characterizing geospatial phenomena based on the geographic context of their neighboring space [44, 18, 8]. Thus far context has been considered as a static snapshot of the neighboring space and spatiotemporal context (i.e. context that changes over time) has received less attention. Although GIScience has been very successful in both quantification of movement and modeling geographic context, the link between *movement*, *behavior*, and *context* has largely been ignored. This also has been identified as a current limitation of GIScience studies on movement [30], and as an important aspect of the future agenda of movement research [38]. Recently, a few studies have tackled the quantification of such connections and interactions [4, 14, 6, 13, 36]. This area still requires a lot of attention in future studies to increase our understanding of the relationships between movement and its *spatiotemporal context*, and to learn how environment influences the *behavior* and accordingly drives movement processes.

4.3 Computational Movement Analysis

The term *computational movement analysis* was coined by P. Laube [29] and is defined as "computational techniques for capturing, processing, managing, structuring, and ultimately analyzing data describing movement phenomena". In GIScience, a large number of studies have pioneered innovative *computational movement analysis* approaches for quantitative assessment of movement trajectories and their similarities [7, 15], mining movement patterns [28], clustering analysis [26], segmentation and classification of trajectories [16], to name but a few. According to recent reviews on the progress of these methods in GIScience [22, 32], most advances in this area have taken place in data mining and machine learning techniques for the detection of movement patterns in moving individuals or groups. The proposed techniques aim at finding structures and associations in movement datasets, by seeking commonalities and arrangements in the geometric specifications of trajectories or in the variation of their movement parameters in space and time [15].

The above publications not only document the significant progress of computational movement analysis in GIScience over the past twenty years, they also highlight the fact that so far environmental factors and geographic context have largely been ignored in the development of methods as well as in analyses. Integrating context and characteristics of the neighboring space in computational movement analysis seems inevitable and a logical step forward for future studies.

4.4 Visualization of Movement

Visualization is a powerful tool in data science for data exploration and discovery of hidden patterns by giving structure to complex datasets through aggregations and cartographic processes. In movement research, visualization and animations enable collaboration among scientists of different domains to find common grounds to discuss movement observations, observe and interpret known patterns, discover unknown structures, and generate scientific hypotheses. Together with *validation*, *visualization* constitutes the backbone of the whole movement research continuum (Figure 1) because it communicates the outcomes of computational techniques, simulations, and predictive models in meaningful and effective ways by portraying the connections between movement and its context. Visualization can also support the validation process by facilitating the interpretation of results and providing real-time feedback for examining movement simulations.

Geographic visualization and visual analytic techniques developed to this date mainly provide a complex representation of spatiotemporal phenomena that is not intuitive [3]. These techniques are often based on the three dimensional Hägerstrand's space-time-cube representation [27, 10] or hierarchical structures of treemaps [40]. Although these static representations can be effective for a small number of trajectories, they are cognitively very complex, particularly, when a large number of long trajectories are involved. Animations have proven to be an efficient medium, specially when communicating movement to scientists of other disciplines [49]. GIScience community should seek to develop more effective ways of communicating patterns in movement datasets using simple, dynamic, and interactive visualization approaches. Context remains to be an inevitable and integral part of future movement visualization tools [31].

5 Modeling Movement Processes

In analyzing trajectories, the assumption is that entities move freely in a landscape and without constraints. This assumption ignores the *internal state* of moving individual (i.e. movement strategies and decisions) and its *behavior*, as well as how it interacts with its physical environment and other dynamic phenomena. It is therefore essential to develop effective modeling and simulation approaches that capture the complexity of movement and behavior of individuals as they relate to the environment in which they move, the other individual with whom they interact and their responses to varying environments [1].

5.1 Modeling and Simulation of Movement

Movement models are "simplified representation of real world" movement processes, which can be used "to explore, to understand better, or to predict" the behavior of such process [9]. These models are generated based on a set of assumptions on the *states* and *behaviors* of moving phenomena and their relationships with their embedding *context*.

In GIScience, the time geography approaches have provided a basis for modeling the space-time settings of movement (i.e. space-time path, prism, and station) mainly for human activity patterns by taking the uncertainty of observations into account [24, 34, 48, 42]. Approaches to date mainly consider movement capacities (i.e. max speed, time budget) when modeling the use of space. However, as mentioned earlier, these models need to be enriched with *contextual* parameters for a more realistic representation of movement processes. Thus far only a few studies have proposed such inclusive agent-based modeling of movement processes [2, 1, 5, 45]. This area still has room for growth in the future of GIScience research.

Traditionally, *simulation models* have been used to generate a set of artificial movement trajectories to test known scientific hypotheses about the behavior of movement processes. Future research should strengthen *simulation models for prediction* purposes based on quantitative analysis of *real movement observations*, and through an iterative *calibration* process.

5.2 Prediction

Our universe is dynamic and changing over time. Any change in the environment can have an impact on the behavior of organisms. Also peculiarities in the behavior of moving phenomena could give us cues about environmental changes. In order to predict future responses to changes and varying environmental conditions, it is critical to translate our understanding of movement processes (i.e. from the right side of the continuum in Figure 1) to inform and calibrate predictive models. As a natural progression of movement research in GIScience, we need to develop *predictive models* to assess *how movement processes are changing over time* and *how future environmental changes impact these processes*. Future simulation models should equip scientists with tools to assess how *changes* of any movement components (Figure 2) influence the susceptibility of the whole system over time. We now have available resources (i.e. valuable observations of real world movement processes and environmental information) and a solid foundation on which to generate effective and integrated simulation models enabling reliable prediction of movement and system outcomes/imbalances.

6 Discussion: Moving from Observations to Predictions

In the past, *direct observation* of moving individuals was the most frequently used approach to quantify movement [47]. Following the rapid growth in movement observations owing to tremendous advances in positioning technologies, analytical methods have enabled GIScientists to increase their *understanding of movement* of dynamic phenomena and their associated *behavior*. However, the investigation of the interactions between moving phenomena with one another and with the physical environment through is lacking. What is required is more research on *context-sensitive analytical techniques and simulation models*. The GIScience community has made significant contribution to the understanding of movement (i.e. transforming *movement observations* to knowledge of *behavior*). These approaches have yet to inform us about how movement is affected by changes in the environment or how behavioral changes influence movement (i.e. derive *movement* from *behavior* and *context*). Still, questions such as *to what extent movement observations convey information on the underlying behavior of moving phenomena? to what degree geographic and environmental contexts influence these behaviors? how susceptible are these behaviors to environmental changes? to what extent changes in the behavior of moving phenomena indicate changes in the environment?* remain unanswered.

In summary, GIScience has been successful in the past at extracting *patterns* and *structures* from *raw movement observations*. However, the community should strengthen its capacities to transform raw movement observations to behavior through informed models by incorporating contextual parameters and interactions with environment (i.e. the right side of the continuum in Figure 1). This knowledge should then inform simulation models in order to *predict* changes in movement in response to changes in environmental conditions (i.e. the left side of the continuum in Figure 1). En route to this goal, several important issues require careful considerations in future directions of movement studies in GIScience, which are summarized as follows:

Temporal scales and granularity of movement: Movement is often reduced to a series of spatial positions in most existing methods, with little attention paid to the temporal scales of movement and observation granularities. Geometric movement analysis techniques often disregard temporal information of trajectories (i.e. temporal resolution and frequencies). Future analytical techniques should take into account the temporal granularity of observations, temporal frequencies of movement patterns, and the sequential structure of trajectories [23, 30, 41].

Movement processes across scale: Movement processes form across different scales in space and time. In order to gain insights into hierarchical structures in movement processes, it is essential to explore movement patterns, their formation mechanisms, and their associations across a range of local to global scales [17, 30].

Movement uncertainty: Uncertainty is a fundamental and unavoidable issue in modeling, simulation, and prediction of movement. As noted in [9], "epistemic uncertainty", which includes "process errors, measurement errors, random individual and temporal effects, uncertainty about initial conditions", greatly affects models and resulting predictions. GIScience has been very successful in modeling measurement errors and making adjustments for locational errors and their propagations through the analysis [48, 42]. Future research should emphasize the effect of uncertainty on modeling and predictions of changes in movement processes.

Evaluation and calibration of models through observations and domain expert knowledge: Future studies should evaluate the strengths and shortcomings of GIScience computational approaches to movement research. Recent studies have shown that GIScience can benefit through interdisciplinary research collaborations [11]. Future movement research should embrace multidisciplinary collaborations to develop informed models by applying domain expert knowledge to effectively evaluate and calibrate models.

A number of important research gaps in computational movement analysis are summarized in [29]. These challenges include *handling big movement data*, *bridging the semantic gap* between low-level movement observations and extracted patterns and structures obtained from the analyses, *safeguarding individual's privacy* specifically in analyzing human mobility, and *generating smart mobile applications* through autonomous and decentralized spatial computing.

7 Conclusions

This article presented a *continuum of movement research* to summarize previous studies and future directions of movement research in GIScience. The continuum organizes movement research in two overarching sections: (1) *understanding of movement processes* and (2) *modeling movement processes*. This article discussed the main highlights of GIScience research across this continuum and suggested a proposal for future directions of movement studies. GIScience to date has made significant contribution to this area through the development of data-driven computational movement analysis techniques and time geography approaches to quantify movement and space use patterns. Still methods to investigate the connections between movement and its *context*, and *interactions* between moving individuals lags behind. The GIScience community should embrace interdisciplinary collaborations with domain experts (e.g. ecologists, health scientists, etc.) to advance its capacities by developing reliable methodologies which are grounded in thorough *knowledge* of the dynamic phenomena and parameterized through real *movement observations*. Movement research in GIScience should progress towards the development of *informed simulations and predictive models* to better understand the behavior of moving phenomena and assess their susceptibility to environmental changes. Issues such as working with *large and real-time* movement datasets, privacy issues, influence of *scale and granularity*, *uncertainty* in movement observations and models, *visualization* of dynamic phenomena remain as important technical and scientific challenges for further research.

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