

Agent-Based Modeling at the Micro-Scale of Urban Environments: A Framework Integrating Imitation in Pedestrian Wayfinding

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Abstract. Previous studies on pedestrian behavior have not fully explored how the presence of others can serve as informational cues about the environment, nor how imitating their choices may act as an effective strategy for wayfinding. This paper presents a framework that integrates imitation into agent-based models of pedestrian movement, addressing the role of social influence in the wayfinding process. Grounded in social psychology, the framework assumes that agents initially lack both a map and specific destinations, requiring them to explore their environment. During this exploration, agents decide on their direction based on factors such as accessibility, attractiveness, popularity, and congestion of available paths. Imitation can be an effective strategy, as other pedestrians might have prior knowledge of the environment. However, this behavior can lead to congestion when too many pedestrians follow the same path. The framework provides a practical approach to modeling pedestrian flows in dynamic environments like temporary markets, fairs, and public events, where navigation is largely driven by exploration and social interaction. By integrating social learning with agent-based modeling, the framework offers new insights for urban design and planning. At the urban scale, it can help urban planners optimize pedestrian flow in high-traffic areas such as tourist attractions, temporary markets, and public plazas. At the municipal and regional levels, it can assist in developing transportation systems by managing pedestrian traffic in transit hubs and public transport terminals, ensuring more efficient and less congested movement across cities and regions.

Keywords: Wayfinding · Pedestrian flow · Social influence · Imitation · Agent-based modeling · Urban Design · Sustainable Urban Mobility

1 Introduction

It is imperative to capture tendencies humans have in spatial behaviors for a better urban/architectural design, which is efficient and safe (Pluchino et al. 2014).

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Understanding pedestrian cognition and behavior is crucial in urban planning, particularly in the design of public spaces and the management of pedestrian flow. Pedestrian movement is often influenced by both individual decisions and social interactions, which makes studying wayfinding behaviors in urban environments essential. Pedestrians frequently rely on cognitive heuristics and social cues, such as the behavior of others, to navigate unfamiliar areas. This social dimension of pedestrian decision-making, though often underrepresented in traditional models, plays a key role in shaping pedestrian dynamics in real-world environments. For example, consider a Christmas market, a typical urban environment where pedestrians may explore without specific destinations, relying on the behavior of others to guide their decisions. Visitors, unfamiliar with the layout, might start by following the busiest paths, assuming that popularity correlates with high-quality shops.

However, their choices are influenced by a balance between imitation, congestion avoidance, and attractiveness of destinations, as well as their perception of crowdedness. In such settings, pedestrians often rely on social influence to navigate, which highlights the importance of modeling pedestrian behavior through agent-based approaches that incorporate these social dynamics. Microscopic modeling of pedestrians' decision making and motion has been one of the common approaches to understanding its nature. Agent-based modeling (ABM) is one of the ways to model a pedestrian's cognition and actions and the resulting pedestrian flow (Helbing et al. 2002; Penn and Turner 2002; Burstedde et al. 2001; Vizzari et al. 2020). With this approach, we can see emergent phenomena resulting from interactions among autonomous pedestrian agents. ABM has successfully shown the dynamics of pedestrian behaviors, and it has been used for practical applications. Evacuation is a popular context where much research has been done on how people find an exit and how to move through the environment to get out of the space (Nishinari et al. 2004). However, some aspects of individuals' spatial behavior have not been a major focus of research. One of them is the social aspect. Imagine you are in a Christmas market that you are visiting for the first time. You want to find some drinks, snacks, and ornaments but do not know where to find them. Unfortunately, a map for this pop-up market is unavailable, so you have to explore the market to find something that interests you by looking at each shop for yourself. You might start exploring by going to the busiest street of the market, assuming that it is popular because there might be many good stores along the street. On the other hand, you might refrain from choosing a crowded path because it can slow down your navigation. Moreover, based on the spatial structure of the environment and the locations of shops you learn through the exploration, you have to weigh the shop options and decide which store to visit.

In the example above, you consider the popularity/crowdedness of each shop as well as its attractiveness. Some shops might be popular because they are selling good commodities. In other words, the popularity of a shop can signal the quality of what they are selling. On the other hand, going to a popular shop means you might also have to wait in a long line to get your drink. In this way, how you explore and exploit the environment is affected by the presence of other people, and this is the social aspect we are going to discuss in this paper.

Behaviors of pedestrians can be divided into three levels: strategic, tactical, and operational levels, which relate to choosing a destination, choosing routes to the destination,

and decisions made to avoid collisions with other people and obstacles, respectively (Schadschneider et al. 2009). Although the operational level of spatial decision making is closely related to how other people move, as seen in collision avoidance, social influences on the other levels have been incorporated into few ABMs (Vizzari et al. 2020; Pluchino et al. 2014; Haghani and Sarvi 2019a). Haghani and Sarvi (2019a) pointed out that there is scarce research focusing on the beneficial/detrimental effects of imitation on pedestrian dynamics.

The goal of this study is to show a conceptual framework for an ABM that incorporates the social influence of other pedestrians at the strategic and tactical levels of pedestrians' decision-making, including imitation. We will explain how social influences and other factors affect people's wayfinding decisions, showing an example decision flow of a pedestrian agent. Moreover, we will discuss the implications of our framework for future pedestrian dynamics research.

In this vein, the paper structure is as follows: We first investigate the preliminary research on the modeling of pedestrians and how the past research dealt with the social aspects of pedestrian behaviors. In discussing the social influences, we show a well-studied theory of behavioral science, such as social psychology. Lastly, we discuss the implications of our framework for future research on pedestrian dynamics.

2 Background

Understanding pedestrian behavior and spatial navigation has long been a central challenge in urban modeling. As cities grow increasingly complex, researchers have turned to computational models to simulate and predict pedestrian flows and behaviors under varying environmental and social conditions in search of suitable frameworks to support evidence-based urban design. In this context, two opposing paradigms converge: top-down approaches, which emphasize spatial configuration and global patterns, and bottom-up approaches, which simulate localized interactions among individual agents (Mara and Cutini 2023). These paradigms are exemplified by space syntax (SS) and agent-based modeling (ABM), respectively — each offering distinct insights into pedestrian dynamics, while also revealing specific limitations.

Section 2.1 briefly analyzes these two contrasting modeling approaches and summarize the main factors considered by previous studies in modeling pedestrian spatial navigation. Section 2.2 then addresses the importance of incorporating social influence into pedestrian behavior modeling.

2.1 Conventional Research on Pedestrian Behavior and Flow

A central challenge in modeling pedestrian behavior lies in identifying which factors to include and how these influence the choice of the most appropriate modeling framework (Mara and Cutini 2023). Two principal paradigms dominate the field: top-down and bottom-up approaches, each with distinct strengths and limitations.

Among the top-down methods, space syntax (SS) has been widely adopted since the 1980s for its effectiveness in predicting pedestrian movement based solely on the spatial configuration of the urban environment. This framework decomposes the built

environment into axial maps, angular maps, or visibility graphs, allowing pedestrian movement patterns to be inferred from the spatial properties of the network itself. SS's strength lies in its ability to reveal how a spatial form conditions behavior without assuming that individuals possess prior knowledge of the environment. This makes it particularly suited for modeling exploration in unfamiliar urban settings, aligning with this study's focus.

Empirical studies have consistently shown that SS metrics, such as axial integration and choice, correlate strongly with observed pedestrian flows, often explaining between 50% and 80% of the variance in movement patterns (Hillier et al. 1993; Penn et al. 1998; Jiang 2009). Its capacity to interpret both material and immaterial urban features further reinforces its value in understanding the social organisation of space. However, SS is inherently static; it lacks a temporal dimension and does not account for behavioral adaptations over time or the influence of social interactions such as congestion avoidance or imitation strategies. These limitations are particularly salient in dynamic environments or contexts involving real-time decision-making, as the one under examination.

To address these deficiencies, bottom-up approaches such as agent-based modeling (ABM) have gained traction. ABMs simulate the actions of individual agents, each capable of perceiving its surroundings, responding to environmental stimuli, and interacting with other agents without central coordination. This paradigm allows for the modeling of micro-level interactions and emergent behaviors, making it highly suitable for heterogeneous, non-stationary scenarios. Even relatively simple models based on cellular automata, such as floor field models, can yield valuable insights into pedestrian dynamics (Schadschneider et al. 2009; Nishinari et al. 2004; Lovreglio et al. 2015). In these models, an agent's next move is determined by a potential field shaped by elements such as obstacles, exits, and the positions of other pedestrians.

Compared to SS, ABM excels in capturing the temporal evolution of movement and the role of social cues in navigation. For instance, Esposito et al. (2020) demonstrate how spatial cognition, environmental features, and social context influence agent behavior in unfamiliar environments. ABM's flexibility comes with trade-offs: the models require extensive and often context-specific input data, are more complex to calibrate and validate, and may suffer from opacity in their internal logic — referred to as the "black box" effect.

Recognising the complementary strengths of these approaches, hybrid models that integrate SS metrics into ABM frameworks have been proposed. Penn and Turner (2002) were among the first to adopt this direction, designing agents whose movement was guided by visibility graph analysis rather than a predefined map. Their model successfully replicated observed pedestrian behavior in a shopping mall, indicating the utility of combining configurational data with agent-based decision-making rules.

More recently, Esposito et al. (2017) discussed how cognitive visualization in urban spaces can play a pivotal role in understanding pedestrian behavior in unfamiliar environments, highlighting the dynamic relationship between spatial elements and human interaction. Understanding human spatial behavior provides a powerful tool for spatial analysis, helping to represent agent interactions and space use patterns, which can inform the development of agent-based models to support decision-making in architectural and urban design (Esposito and Abbattista 2020).

While both SS and ABM can effectively capture spatial use and flow dynamics (Mara et al. 2024), modeling ex-tempore movement in unfamiliar environments requires refining ABMs with governing laws that incorporate social influence mechanisms. Such an approach allows the model to go beyond static predictions and incorporate adaptive, interaction-driven decision-making processes. This integration not only enhances model realism but also aligns with contemporary shifts towards digital twins and computationally enriched urban modeling (Wan et al. 2023; Papyshev and Yarime 2021).

2.2 Importance of Incorporating Social Influence

Here, we show the importance and effectiveness of modeling social influence from the perspectives of social psychology and collective spatial behavior. Dalton et al. (2019) argued that wayfinding, which is a plan of routes to one's destination, is a social phenomenon, but that research on this "social wayfinding" is scarce. They showed different types of social wayfinding strategies, including the one where surrounding others can be informational cues about the place you are located in. For example, when you are in an unfamiliar place but share the same destination with other people, just following them can lead you to your destination if some of them know where it is. In this case, you can reach your goal without a complete map of the environment (Dalton et al. 2019).

Some of the past research has incorporated social influence into agent-based modeling of pedestrian wayfinding. Vizzari et al. (2020) implemented imitation in their model where pedestrians are attracted to a path to which preceding others suddenly switch. In other words, they change their path plan by following others. However, this imitation is just a part of a broader range of imitation behaviors in wayfinding.

Moreover, most of the research assumed that pedestrian agents have a complete map of the environment or at least knowledge about where their destination is, and specific destinations are determined at the beginning of simulations. This is the case with the model of Vizzari et al. (2020), where agents knew where their destination was. A situation where pedestrian agents have neither a map nor a specific destination and thus need to explore the environment has not been considered. In this kind of scenario, pedestrians may use different wayfinding strategies as they do when they have a map and a destination. Therefore, it is worth investigating this novel setting, where pedestrians do not have enough information about the environment.

The use of social information can be beneficial in this case. Social influence on people's decision making has been studied in behavioral sciences such as social psychology. Humans show tendencies to imitate other people or give in to peer pressure. A famous empirical example of it is the cognitive task of Asch (1951). In the experiment of the study, participants were asked to choose among three lines the one whose length was the same as that of a reference line. Although the answer was clear, some of the participants chose the same line as the wrong majority, who were working for the experiment and chose the wrong line on purpose, showing a conformity tendency. This conformity is a product of normative influence and informational influence. The former means that one tries to maintain belonging to their group, while the latter means one tries to be correct in their decision making (Deutsch and Gerard 1955). A theory closely related to the latter is social learning theory (Bandura and Walters 1977). Simply put, it is a

theory that people learn by observing and imitating others. What others are doing can give people what to do in the situation they are in. According to Laland (2004), a social learning strategy is not always beneficial, and from whom and when one socially learns is important. For example, copying successful individuals, copying the majority, and copying when uncertain are a few of many social learning strategies (Laland 2004).

Social influence on decision making has been investigated in exploration/exploitation tasks. A multi-armed bandit task has been used to study this type of exploration/exploitation behavior (Toyokawa et al. 2014; Toyokawa et al. 2019). In this task, people need to explore an unfamiliar environment composed of something like slot machines that give those who choose a machine a reward. Potential reward can vary across slot machines because they have different reward distributions; some slot machines are more likely to give a person a higher reward than other slot machines. These distributions are initially unknown, so people need to try different machines to learn about the distribution, which is exploration. On the other hand, it is beneficial to choose (exploit) one machine that is the most likely to return the highest reward to optimize its performance. Spending a lot of time on exploration means little time available for exploitation and vice versa. Therefore, it is necessary to hit the balance between exploration and exploitation. Past empirical research showed that social learning strategies can have both positive and negative effects on performance, depending on conditions. In experiments using this task, people showed social learning/imitation tendencies when choices of other people in the same environment were observable (Toyokawa et al. 2014; Toyokawa et al. 2019). In spatial behavior, it can be said that deciding where to go corresponds to exploration and heading to the destination corresponds to exploitation. Following other pedestrians is compatible with imitation in the multi–armed bandit task.

Although it is context-dependent, humans have a tendency to imitate or socially learn from other people's behavior, and it can be beneficial in an uncertain environment where people need to learn optimum behavioral strategies. We believe that in human spatial behaviors, this kind of imitation is relevant and that the incorporation of this tendency can contribute to improvement in the modeling of pedestrian behaviors.

As mentioned above, there is some research on modeling social influence on pedestrians, but they commonly assume that pedestrians have a map of the environment and their destination. This means that a situation where people are not familiar with the environment and thus need to explore has not been accounted for. We will deal with this kind of situation hereafter. The idea of hitting a balance between exploration and exploitation, studied in research on social learning, will help conceptualize the pedestrian behaviors in a scenario where people do not have a map and destination initially.

3 Integration of Social Influence into Agent-Based Modeling

In this section, we propose how to implement social influences in agent-based modeling of pedestrian wayfinding behavior in an uncertain environment. We start by showing empirical and theoretical findings that support the dynamics. Then we explain the potential interplay among different factors affecting pedestrians' wayfinding. Lastly, we propose agents' decision rules with a conceptual framework based on the interplay.

3.1 Theoretical Interplay Between Different Factors

Some of the past research has investigated social influence on wayfinding in both a theoretical and an empirical manner. Chiou and Bayer (2021) conducted an agent-based simulation of pedestrians in a night market in Taiwan, implementing the attractiveness of each shop and behavioral rules based on space syntax. As one can expect, people who had preferences about destinations moved towards shops that were more attractive to them, leading to the formation of clusters in front of popular shops. This phenomenon was observed in an empirical case study in the night market as well. People approach more accessible and attractive places and increase the density of the spot as a result. On the other hand, they also revealed pedestrians' tendency to avoid congestion regardless of the high attractiveness of shops.

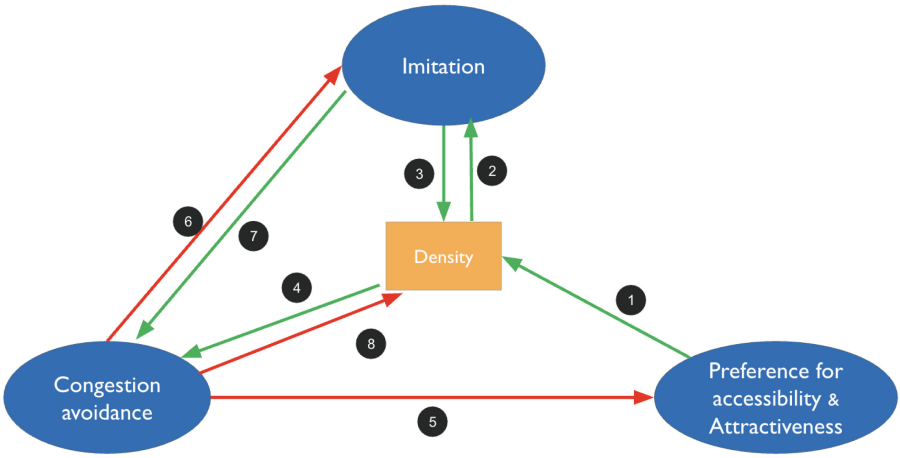
Although it is a study of ants, ants escaping symmetric space showed imitation tendency until the density of the followed way goes up to some degree, but then the imitation tendency disappears as the density increases more (Li et al. 2014). This suggests there is a kind of threshold for density or crowdedness above which imitation stops and congestion avoidance happens.

Vizzari et al. (2020) implemented congestion avoidance in their simulation model. This decision is based on subjective crowdedness. Moreover, imitation behavior is integrated into the model. Imitation in their study considers the following behavior that happens when sudden directional changes of preceding agents are made. Their model succeeded in replicating the observed data in experiments of Crociani et al. (2016). However, this is not an imitation at the level of the planning path before an agent starts moving.

In evacuation experiments, Haghani and Sarvi (2019b) showed that people tend to avoid following the majority when they escape the environment, rather than imitating and choosing the same path as others to shorten escape time.

In this way, wayfinding or route choice behavior involves different factors, both social and physical, and how these factors interact with each other affects the resulting pedestrian flow. The past research introduced above pertains to pedestrians' tendency to have preferences for destination, avoid congestion, and imitate other pedestrians' route changes. They can influence the collective pattern of people moving around the environment, including where and when congestion occurs. Even more, pedestrian flow driven by these factors can directly relate to their economic behavior, such as where to buy something when they are shopping. This kind of effect is to be investigated in future studies.

Next, let's look at the whole picture of the interactions between different factors affecting the pedestrian decision makings mentioned above. Figure 1 shows a theoretical framework for the interplay among different factors related to wayfinding. The arrows show the direction and types of effect each factor has on others. The green arrows express positive feedback, while the red ones express negative feedback. The basic structure of this figure is that behavioral/psychological tendencies written in the blue bubbles affect density as a physical phenomenon, and conversely, the density affects the behavioral/psychological rules. Also, each behavioral/psychological rule can boost/hinder one another. The numbers next to each arrow correspond to the following explanation about the effect that each factor has.



Code in Fig.1	Statement	Reference
1	Accessibility and Attractiveness increases Density	Chiou and Bayer (2021)
2	Density reinforces Imitation	Li et al. (2014)
3	Imitation increases Density	Li et al. (2014)
4	Density reinforces Congestion avoidance	Vizzari et al. (2020)
5	Congestion avoidance reduces preferences for Accessibility and Attractiveness	Chiou and Bayer (2021)
6	Congestion avoidance weakens Imitation	Haghani and Sarvi (2019b)
7	Imitation reinforces Congestion avoidance	Vizzari et al. (2020)
8	Congestion avoidance reduces density	Haghani and Sarvi (2019b)

Fig. 1. Interplay of key factors influencing pedestrian wayfinding behavior: The diagram illustrates how Imitation, Congestion Avoidance, and Density interact to shape pedestrian decision-making in dynamic urban environments. The table below the diagram provides a summary of empirical research that supports the influence of each factor on pedestrian flow, highlighting their relationships and impact on wayfinding strategies. The numbers by each arrow correspond with the above-mentioned past research. Preference for accessibility and attractiveness are combined in one bubble in the diagram because they are both static preferences.

"Imitation" is a behavior of following other pedestrians, such as taking the same path as others. "Congestion avoidance" is a behavior of refraining from going on a path when a pedestrian perceives congestion in it. "Preference for accessibility & Attractiveness" is a behavioral tendency to approach a more accessible path, as analyzed in space syntax, and to approach a more attractive path. Here, being "attractive" means that the spots along the path seem to be offering something interesting to a pedestrian, and thus the path as a whole looks interesting. For example, seeing a billboard for a hot chocolate shop can attract those who are looking for a drink in a Christmas market, and they might choose the path over others.

Below are the explanations of each effect expressed by an arrow. The numbers in the parentheses below correspond to the numbers by the arrows in Fig. 1.

People prefer paths and spots that are accessible and attractive (arrow #1, Chiou and Bayer 2021). For example, in a Christmas market, it is reasonable to think that people

can easily find and get attracted to the shops selling interesting goods along the main street. This phenomenon is empirically and theoretically demonstrated by Chiou and Bayer (2021), as referred to before in this section.

People follow the majority of people choosing one path, expecting them to know, if not completely, about the environment, and to lead them to a good spot (arrow #2, Li et al. 2014). This is the same type of imitation tendency as the one social leaning studies have investigated (Bandura and Walters 1977; Laland 2004; Toyokawa et al. 2014; Toyokawa et al. 2019). Dalton et al. (2019) argued that this kind of social effect can happen in pedestrian wayfinding, but empirical results are scarce. As an indicator of "majoritiness", we use density as a parameter here.

When many people imitate leaders, the chosen path gets denser, which is a herding behavior (arrow #3, Li et al. 2014). And when the path gets too dense and people feel crowded, they start avoiding congestion by taking other paths (arrow #4, Vizzari et al. 2020). Li et al. (2014) showed empirical support for the phenomena of (arrow #3, Helbing et al. 2002) and (arrow #3, Penn and Turner 2002). Also, the simulation of Vizzari et al. (2020), which introduced congestion avoidance, replicated empirical data taken in an experiment in the same environmental setting as the simulation. These tendencies are reasonable in that pedestrians take advantage of proceeding pedestrians ahead while avoiding being stuck in a crowd.

As Chiou and Bayer (2021) showed, congestion avoidance temporarily deteriorates the effect that accessibility and attractiveness have when avoiding a crowd is prioritized (arrow #5, Vizzari et al. 2020). Likewise, since congestion avoidance has become the pressing goal, people stop following the populated path (Li et al. 2014; Haghani and Sarvi 2019b). While the arrow numbered (arrow #4, Penn and Turner 2002) illustrates why congestion avoidance occurs (arrow #5 and #6, Nishinari et al. 2004), describes one of the results that congestion avoidance can bring about.

This congestion avoidance can be boosted by imitation (arrow #7, Vizzari et al. 2020); people follow others who are trying to get away from the crowd to find a less congested route (Vizzari et al. 2020). As a result of congestion avoidance, the density decreases, and the crowdedness becomes lighter (arrow #8, Haghani and Sarvi 2019b). It is noteworthy that congestion avoidance does not occur until the density level goes above a threshold. Therefore, the interplay among the factors in Fig. 1 may look different when congestion is happening and when it is not. For example, congestion avoidance does not happen and arrows with numbers from 4 to 8 are not in effect when an agent does not perceive crowdedness.

3.2 A Conceptual Framework for Agent-Based Modeling

Here, we show a set of basic rules a pedestrian agent will follow when it is exploring an unfamiliar environment, initially having no specific destinations. This type of uncertain situation is worth studying because of its universality.

Pop-up markets, such as Christmas markets, are one example. It often happens that first-time visitors come into the market and enjoy buying commodities there by exploring the market. With time and economic constraints, visitors need to explore the environment efficiently. Social factors can play a huge role in their decision of which direction to go because there is not much other useful information available. Museums where visitors

can choose what to see in what order are a similar situation. Tourist spots can be a similar situation too. For example, suppose a tourist comes to a historic town that is popular among tourists and wants to find photogenic spots. She does not know much about the town because she just stopped by it. In such a case, it might be a good idea for her to follow other tourists-like people because they might have better knowledge about the environment and they can lead her to a stop with a good view of the town.

These examples are just a few of the situations where imitation in wayfinding can be beneficial. Understanding how people move around in these cases and what macro-level results, such as pedestrian flow and congestion, can occur is useful in many ways, including the design of urban environments and buildings as well as crowd management.

Hereafter, we show specifically how pedestrian agents can make wayfinding decisions and how they decide their destination. Figure 2 shows a model of how pedestrian agents make decisions to explore an environment and choose which specific spot, such as a shop in a market or an exhibit in a museum, to head for. When an agent does not have a specific destination in the area, it first has to explore the environment to see what kind of spots are where and what is offered within each spot. As it learns, if not all, about the environment, it can decide which specific spot to reach.

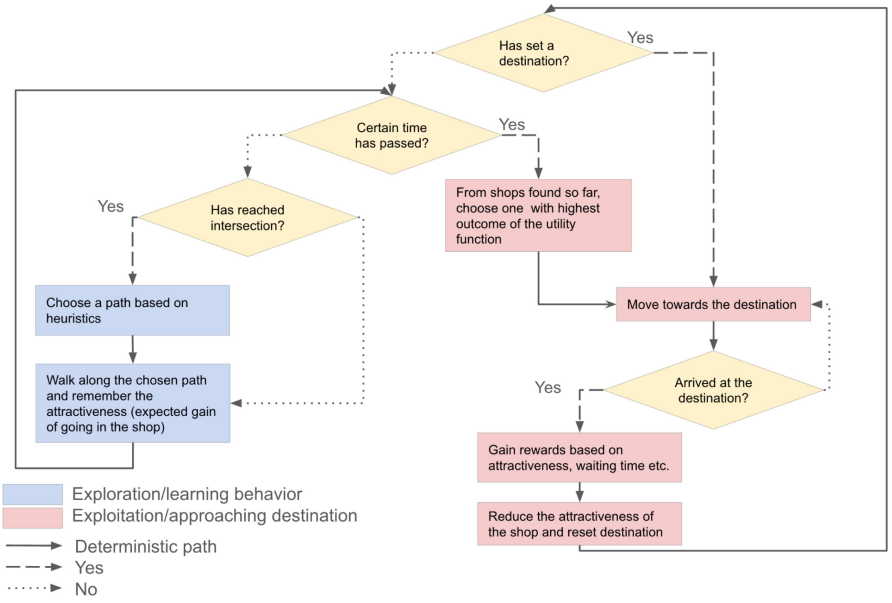


Fig. 2. Pedestrian decision-making flow chart: This flowchart demonstrates the decision-making process of a pedestrian agent as they transition from exploration (heuristic-based path choice) to exploitation (destination-oriented behavior). The chart outlines the steps of path selection, exploration, and the eventual settling on a specific destination, based on utility calculations. The chart outlines key decision-making processes. The arrows represent the movement from one decision point to the next, where the agent reevaluates its path based on social cues and congestion levels. The yellow boxes indicate points where the agent checks its state. This figure was developed by the authors to illustrate the model's approach to wayfinding behavior in uncertain environments.

In the present research, we assumed this path choice is driven by heuristics (we will discuss destination choice later). Heuristics are simple behavioral rules that lead the decision maker to a reasonably good/accurate decision. When pedestrians do not have much useful information for their decision making process, they can use heuristics (Tong and Bode 2022). Heuristic strategies for exploring behavior include imitating the majority, choosing the most accessible or attractive option, and avoiding congestion, as illustrated in Fig. 1. How people switch from one heuristic to another is to be studied in the future, but it is reasonable to think the timing of switching depends on density level or perception of crowdedness. Indeed, Li et al. (2014) and Haghani and Sarvi (2019b) suggested that switching from imitation to congestion avoidance depends on density/crowdedness. Substantially more research is required on this matter, but the density-dependent rule can be a plausible mechanism that accounts for the choice of heuristics.

After some time for exploration, an agent decides which spot to visit, corresponding to exploitation. This means that an agent sets a destination. Decisions in this phase are influenced by social information as seen in wayfinding. We assume this decision is based on a utility function, as an agent now has some knowledge about the environment. The function takes a spot, such as a shop in a market, as input and calculates its expected outcome by summing the effects of the spot's attractiveness, popularity, estimated travel time, and estimated wait time. The last component represents situations where an agent must wait in line, such as queuing for hot chocolate at a popular shop in a Christmas market.

Once an agent reaches their destination, it gains and remembers the collected reward (the utility of the shop and commodity) and then reduces the attractiveness of the spot since it is reasonable that buying something from the same store over and over again is not as exciting as the first time. Rather, we assume that it is more favorable to try different spots. Therefore, the agent starts exploring again after resetting the destination.

The key parameters influencing agent behavior in this model include imitation thresholds, density thresholds, and heuristic switching conditions. Future work will aim to define and calibrate these parameters based on real-world data, ensuring the model's replicability and accuracy in diverse urban settings.

4 Discussion

Pedestrian behaviors in an uncertain environment have not been thoroughly investigated in past literature (Haghani 2019b). Additionally, the assumption that pedestrians always have a specific destination has been a common and simplifying one. In this paper, we have discussed imitation behavior as a form of social influence that can occur in uncertain situations where pedestrians do not have a predefined destination.

This paper explained how different behavioral tendencies, such as imitation, congestion avoidance, and preference for accessible and attractive paths, interact with each other. Density, or the perception of crowdedness, can moderate these factors. The interplay among these factors has an empirical background, which helps us argue for the plausibility of our framework. As shown in Fig. 1, the relationships between imitation, congestion avoidance, and density form the foundation of the agent decision-making process, illustrating how these factors influence one another in the model.

We showed an example decision flow of a pedestrian, as in Fig. 2. The key takeaway is that the exploratory wayfinding behavior, which continues until a specific destination is set, and the behavior of heading towards a determined destination involve different processes. Figure 2 illustrates the decision flow of pedestrians transitioning from exploration to exploitation, where initial path choices are driven by heuristics before settling on a destination. After visiting the destination, agents switch again to exploration until they set a new destination.

The decision making for exploration is based on heuristics, while the choice of a destination is driven by the calculation of the utility of each potential destination. Pedestrians often rely on heuristics when making decisions in uncertain situations (Tong and Bode 2022). Therefore, it is reasonable to assume that pedestrians make heuristic decisions in the exploration phase, while they calculate the utilities of each spot during the exploitation phase, which is a phase when they head towards a specific destination. However, more empirical research is necessary to understand when pedestrians switch between different heuristics.

We also want to emphasize the benefit of using space syntax-based heuristics as a baseline heuristic behavior for pedestrians in the situations we have discussed. Space syntax can function without agents needing a complete map or specific destination, offering a simplified yet effective approach to modeling pedestrian behavior.

This model enhances traditional pedestrian flow models by integrating social influences into agent-based simulations, filling a gap that has been underrepresented in existing frameworks. Unlike conventional models, which assume pedestrians have predefined destinations or full knowledge of their surroundings, our model accounts for situations where pedestrians are unfamiliar with the area and rely on social cues to navigate. By focusing on pedestrian decision making in uncertain environments, this framework offers urban planners a more dynamic and nuanced understanding of pedestrian behavior. It is especially applicable to complex environments like temporary markets, fairs, and public events, where social interactions heavily influence wayfinding decisions. This approach provides a significant advancement over current pedestrian simulation models by capturing the complexities of crowd behavior and social learning in public spaces. Urban planners can use these insights to design spaces that accommodate both individual navigation needs and collective movement patterns, optimizing pedestrian flow and improving safety.

While we have focused on imitation as a form of social influence, there is significant potential to expand the model. New behavioral rules can be added to the decision flow shown in Fig. 2. For example, we can take advantage of heuristics people use in an optimal stopping problem, where people encounter different options sequentially and cannot come back to the same one thus they need to decide whether they take the current option or not in a timely manner (Baumann et al. 2020). This corresponds to a situation in a Christmas market where there is a possibility of goods getting sold out, and the visitor decides to buy one right now or misses it forever. Further agent interactions, such as cooperation or conflict among pedestrians, can be included in the model as well, especially at the operational level.

To enhance the realism of the model, it will be beneficial to introduce heterogeneous agents with different cognitive and behavioral profiles. For example, tourists may rely

more heavily on social cues such as popularity or density, while locals might be more independent in their decision-making. Different people might have different thresholds for density and popularity as well. Additionally, demographic variables, such as age or walking speed (e.g., elderly pedestrians or children), could influence decision-making processes and path choices. Incorporating these factors could further improve the model's ability to simulate pedestrian behavior in diverse urban settings.

5 Conclusion

We proposed a way to expand agent-based modeling of pedestrians by integrating social influence in the form of imitation, an aspect that has not been a major focus in past literature. We introduced a new scenario where imitation plays a crucial role; an uncertain environment where pedestrians do not have an initial specific destination. In this situation, pedestrian agents take advantage of the behaviors of others, such as the paths they take, to explore the environment more efficiently. The inclusion of social influences, such as imitation and crowd behavior, enhances our model by simulating more realistic pedestrian decision-making processes in dynamic environments. This framework provides urban planners with a tool to better manage pedestrian traffic and prevent overcrowding, especially in high-density environments.

Further empirical research is necessary to explore how pedestrians choose paths and destinations, which will be crucial for model calibration and validation. Through this process, we will be able to model more plausible pedestrian dynamics and refine the framework further. Future research directions could include applying this model to different cities and more complex urban environments, paving the way for additional refinement and expansion of pedestrian dynamics models to address a broader range of challenges in urban planning.

In future research, empirical data from diverse real-world urban environments, such as crowded markets, festivals, transit hubs, and commercial districts, could be used to validate and refine the model's accuracy. By testing the model under varying conditions, it can be further developed to better reflect real-world pedestrian dynamics and help urban planners optimize pedestrian flow in diverse settings, reducing congestion and improving the overall visitor experience. The ability to simulate how pedestrians interact with one another, observe the decisions of others, and adjust their paths based on social cues gives planners a dynamic tool to address complex real-world challenges in urban spaces. Furthermore, this framework can be applied in micro-urban analysis to monitor pedestrian movement dynamics on central streets, where high densities may occur, and it is also adaptable for urban transportation systems — including transit hubs and public transport terminals, where real-time adjustments based on crowd movement could enhance operational efficiency and reduce congestion.

The integration of real-time data, such as IoT sensors, could significantly enhance this framework by providing dynamic information on crowd density and path popularity. This would allow for real-time adjustments to pedestrian flows, making the model more adaptive to changing conditions in urban spaces. Future research could explore how such data could be incorporated to improve the responsiveness of pedestrian management systems in large-scale urban environments.

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